

## Forecasting the Impact of an 1859-calibre Superstorm on Satellite Resources

Sten Odenwald<sup>1,2</sup>, James Green<sup>2</sup>, William Taylor<sup>1,2</sup>

1. QSS Group, Inc., 4500 Forbes Blvd., Lanham, MD 20706

2. NASA, Goddard Space Flight Center, Greenbelt, MD 20771

*Submitted to Advances in Space Research: June 30, 2005*

### Abstract:

We have assembled a database of operational satellites in orbit as of 2004, and have developed a series of simple models to assess the economic impacts to this resource caused by various scenarios of superstorm events possible during the next sunspot cycle between 2010 and 2014. Despite the apparent robustness of our satellite assets against the kinds of storms we have encountered during the satellite era, our models suggest a potential economic loss exceeding \$10<sup>11</sup> for satellite replacement and lost profitability caused by a 'once a century' single storm similar to the 1859 superstorm. From a combination of power system and attitude control system (the most vulnerable) failures, we estimate that 80 satellites (LEO, MEO, GEO) may be disabled as a consequence of a superstorm event. Additional consequences may include the failure of many of the GPS, GLONASS and Galileo satellite systems in MEO. Approximately 98 LEO satellites that normally would not have re-entered for many decades, may prematurely de-orbit in ca 2021 as a result of the temporarily increased atmospheric drag caused by the superstorm event occurring in 2012. The \$10<sup>11</sup> International Space Station may lose at least 15 kilometers of altitude, placing it in critical need for re-boosting by an amount that is potentially outside the range of typical Space Shuttle operations during the previous solar maximum in ca 2000, and at a time when NASA plans to decommission the Space Shuttle. Several LEO satellites will unexpectedly be placed on orbits that enter the ISS zone of avoidance, requiring some action by ground personnel and ISS astronauts to avoid close encounters. Radiation effects on astronauts have also been considered and could include a range of possibilities from acute radiation sickness for astronauts inside spacecraft, to near-lethal doses during EVAs. The specifics depends very sensitively on the spectral hardness of the accompanying SPE event. Currently, the ability to forecast extreme particle events and coronal mass ejections, or predict their fluences and geo-severity in the 24-hrs prior to the event, appears to be no better than 50/50.

If the events of the 1859 superstorm serve as a guide, the scope of a contemporary superstorm will most certainly be an awesome event, but one that the vast majority of our other satellite resources may reasonably be expected to survive.

## 1.0 Introduction

Satellites appeared to be remarkably robust against most space weather events encountered during the last 30 years, however, recent studies of historical events show that even more violent solar and geomagnetic storms are possible for which we have, as yet, not experienced during the space age. A recent study of historical solar storms by *Cliver and Svalgaard* [2005] compared more than 50 major storms identified by their geomagnetic indices, Solar Proton Events (SPEs), and Coronal Mass Ejection (CME) speed. One storm stands out as the most impressive of all, namely the August-September 1859 superstorm event described in considerable detail by the Editors of the *American Journal of Science* [1859; 1860] and by *Loomis* [1860, 1861] and more recently by *Tsurutani* [2003]. It is often called a 'superstorm' because of its remarkable strength (white-light solar flare and  $D_{st} < -1700$  nT) and global impact. Meanwhile, studies of Apollo lunar rock samples by *Reedy* [1998] suggest that during the last few million years, occasional solar events of perhaps 3-fold greater strength than the 1859 storm may have occurred based on radioisotope upper limits. In the discussion to follow, we will consider this 'upper-limit event' to be the worst-case superstorm for our analysis.

Considerable attention has been paid to the many ways in which space weather can compromise satellite operations. For a general overview see *Odenwald* [2000; 2005]. In addition, *Baker* [1986] and *Allen and Wilkinson* [1993] have assembled and analyzed satellite anomaly databases. *Belov et al.* [1999] and *Lucci et al.* [2005] have analyzed these, and other, anomaly databases in the context of various space weather drivers. By coupling the growing knowledge of historical extreme space weather events (e.g. 'storms') with the known mechanisms that lead to satellite anomalies, malfunctions and loss of service, it should now be possible to ask what economic impact a worst-case superstorm might have on our satellite resources. The answer to this question may suggest strategies for mitigating these potentially costly effects.

This paper will define an approach to estimating the economic consequences of a space weather superstorm, and derive rough cost and service disruption estimates for several worst-case scenarios based on what we know, or suspect, about superstorm dynamics. Although many important factors are currently missing from this model, or unavailable in the public literature, the intent of this effort, nevertheless, is to go a step beyond the current informal estimations and provide a new framework for quantitatively assessing these impacts. This approach will also reveal areas of research that might make subsequent economic impact models more robust.

The paper is organized as follows: Section 2 reviews the scale of the satellite resource; Section 3 discusses the economic dimensions of the commercial satellite resource; Section 4 quantifies, so far as is possible, the likely space weather influences that can be expected to play a dominant role in satellite functioning following a worst-case superstorm event; Section 5 assesses the

consequences of these influences through a series of simple models; and in Section 6 we will draw conclusions based on these models by providing a possible scenario for a superstorm.

## 2.0 The Satellite Database

As a consequence of the monthly launches of new satellites, and the ongoing retirement of existing satellites, the number of operating satellites is constantly changing. Estimates found in the literature range from 300 operating satellites according to *Todd* [2004], to 700 according to *Spotts* [2003]. The database that forms the basis for this paper's impact modeling was assembled from over two dozen online resources (e.g. Sat-ND.com, Space-Track.org, LyngSat.com, The Satellite Encyclopedia, Encyclopedia Astronautica), along with over 200 press releases, corporate financial statements, and government reports. By inter-comparing these resources to remove redundancies and in some instances misspellings, we were able to uniquely identify a total of 3,873 satellites including both working and non-working systems as of December 2004. Of these, 1,621 satellites had previously re-entered the atmosphere according to *Space Track* [2005], leaving 2,252 satellites still in orbit in the working and non-working categories. As a point of reference, in 2005 the US Space Command tally for the number of orbiting bodies identified as 'payloads' [*Space Track*, 2005] was 3,048 not including re-entered satellites. This number is larger than our estimate of still-orbiting satellites (2,252) since the term 'payload' can mean a variety of different objects delivered into space including dummy masses. Many of the still-orbiting satellites include systems such as communication satellites that have been placed in graveyard orbits and are no longer in service. Reports of detailed satellite retirements are difficult to obtain for the commercial satellite sector, and nearly impossible to obtain for military systems. For this reason, we have decided to eliminate systems that are substantially older than reasonable planned lifetimes for the particular satellite system.

From the collection of 2,252 satellites we eliminated satellites that were more than twice the published lifetime of the satellite. This is a fair criterion to adopt since, for example, communication satellites are seldom used past their planned retirement age due to the advance of more profitable technology in newer satellite designs. For example, GLONAS satellites launched in 1995 with lifetimes less than 3 years were eliminated, as were the NOSS, Oko and Picosat satellite series for similar reasons. We also eliminated a variety of test satellites with planned 1-2 year lifetimes such as Miranda, Oderacs, and Strela. From this assumption, we estimate that 936 satellites are apparently still working as of December 31, 2004. The current tally is believed to be complete to about +/- 5%, with the operational status of military satellites being the largest source of the uncertainty. A complete catalog of these satellites has been developed by *Odenwald* [2005].

In Table 1, we summarize the tallies of satellites for each category and orbital location. LEO (Low Earth Orbit) satellites have orbital perigees below 2,000 km;

GEO (Geosynchronous) satellites are located at 35,768 km, and MEO (Mid Earth Orbit) are found between 2,000 km and 35,768 km. Operating satellites above GEO orbit are not considered in this study.

### **3.0 Satellites as an Economic Asset.**

There are two components to this calculation of economic value: 1) the actual satellite hardware and launch costs; and 2) the resource value returned by the satellite during its operational life. Both must be considered as elements of a replacement cost if the satellite is disabled. The first of these is by far the easiest to estimate, though there are some ambiguities in the definition of the term 'cost'.

When satellite costs are published, they often appear in one of at least three possible forms: 1) Satellite hardware cost alone; 2) hardware plus launch cost; or 3) satellite 'cost' plus operations and insurance. Generally, little attempt is made in the literature to distinguish between these possibilities in a consistent way. The resulting ambiguities can, for example, cause a 30% variance in the quoted price of a GEO satellite.

Of the 936 operating satellites, our database contains actual published costs for 436 satellites collected from hundreds of web-based press releases and related sources. For satellites (specifically military systems) where such costs could not be uncovered, we estimated a cost based on published estimates for the particular satellite model (e.g. Galaxy, Iridium, GPS or bus type). If the satellite model could not be determined, we assumed a cost based on the satellite's mass and orbit location. For example, from a survey of various satellite systems at LEO, MEO and GEO, the median price per kilogram for a satellite is \$70k at MEO and \$178k at GEO. LEO satellites are far more diverse in function and cost than other satellite because these systems include 1 kg nanosatellites as well as 14,000 kg military surveillance satellites. For example, the LEO price per kg is \$65k with Iridium and Globalstar satellites included, and \$455k without Iridium and Globalstar included. The later cost is strongly biased in favor of large systems such as the Hubble Space Telescope and various DoD payloads.

The estimated replacement cost (satellite plus launch) for the entire working satellite population as of the end of 2004 is about  $\$1.9 \times 10^{11}$ , of which about  $\$5.5 \times 10^9$  appears to be launch cost. Given that only half of the satellites had published costs, and that the price variance for the unreported systems can be up to 30%, the total replacement cost is likely to range from  $\$1.7$  to  $2.3 \times 10^{11}$ . Figure 1 shows that half of the existing satellite resource, representing an investment of about  $\$10^{11}$ , is older than five years, and 181 satellites representing about  $\$4.3 \times 10^{10}$  are at least 10 years old and in most cases due for retirement.

Beyond the obvious national security importance of maintaining a large military satellite asset, the civilian satellite industry represents a major source of economic activity supported entirely by the 691 research, communications, imaging, and weather satellites currently in orbit. The satellite communications

industry by 2002 was already worth  $\$8.68 \times 10^{10}$  annually [Space.com, 2003] and represents the largest element of the civilian economic sector that relies wholly on the availability of satellite resources. This leads to the conclusion that approximately  $\$2.5 \times 10^8$  of business per day derives directly from satellite-related services and profits.

As for the second component to our asset calculation, we can assess the resource value generated by a satellite once we have determined which elements of the satellite generate the profit. For communications satellites, this usually depends upon the number of transponders in operation and their cost to lease. From Table 2 we see that the average transponder is leased at about  $\$2 \times 10^6$ /year [VSAT, 2005].

From the known transponder information for 235 of the 308 operating GEO satellites, we estimate that by December 2004, the 235 satellites and their 6,841 transponders have generated approximately  $\$7.4 \times 10^{10}$  during their 36,700 transponder-years of operation. Figure 1 shows the cumulative value of our existing GEO satellite assets, including both the replacement cost, and the profit generated by those systems with transponders. By 2004, this population has generated about  $\$10^{11}$  in profits since launch, or approximately  $\$10^{10}$  annually by 2004. Note that the cumulative replacement cost is equal to the cumulative profit for satellites currently older than 4 years. Younger systems have not had enough time to 'break even' since launch.

## 4.0 Modeling

Despite the obvious importance of our satellite resources, so far as we could determine, there has not been a systematic and detailed attempt to determine the global economic losses to this system of satellites from space weather effects. There are many informal opinions about the consequences of such space weather impacts across the entire satellite resource, but no rigorous attempt to quantify these opinions, or base them on realistic models. A major impediment to creating such a detailed prediction is that the commercial satellite community does not publish details on the profitability or losses incurred by their satellites. Moreover, the impacts to satellite systems by space weather events of any kind are rigorously kept from the open literature due to the very real concern that such reports will impact investor/client confidence. Generally, the detailed manner by which a space weather event translates into a specific gain or loss in profit is a matter for conjecture. Nevertheless, there are a number of factors caused by space weather that are known to materially affect spacecraft operations, and these can be quantified. They are: solar power erosion, single event upsets and spacecraft anomalies, and orbit decay. These factors will be analyzed in the next three sections.

### 4.1 Solar Power Erosion

All satellites require solar-electric power to operate. Solar panel power is degraded by cosmic rays at a steady rate each year, and this effect is usually

built into the design of the solar panels. SPEs also cause solar panel degradation by significant amounts over times scales as short as a few hours. Because their magnitude (fluence) and onset are largely unpredictable, they represent a significant source of uncertainty in spacecraft solar panel design.

The pre-launch lifetime estimate for a satellite is usually based on the ~ 2% per year decline in satellite operating power due to cosmic rays following the analysis of *Chetty* [1991]. Satellites in MEO orbits within the Van Allen Belts can, however, experience ~5% power losses annually according to *Patel* [2000]. Typically, satellite lifetimes since 1995 are considered to be nearly 15 years, and satellites are commonly amortized on this basis. SPEs change this calculation by accelerating the erosion of the solar panels at a rate far faster than the planned-for cosmic ray component. Each year a satellite does not survive to its expected end-of-life (EOL) results in a significant loss in revenue.

A list of SPEs and their fluxes between 1976 and 2004 was obtained from NOAA [2004]. Table 3 summarizes this SPE history in terms of the peak fluxes of the strongest events each year, along with its date and associated flare. The SPE fluxes are integral 5-minute averages for protons with energies >10 MeV, given in particle flux units (pfu), measured by GOES spacecraft at geosynchronous orbit. (1 pfu = 1 proton cm<sup>-2</sup> sr<sup>-1</sup> s<sup>-1</sup>).

The SPE flux history can be compared with the SOHO power degradation shown in Figure 2, adapted from *Brekke* [2004]. We have modeled the power loss by assuming a simple combination of cosmic ray and SPE effects according to:

$$\text{Power (\%)} = 100 - \alpha T - (C/\beta)$$

Where T is the number of 6-month intervals since launch and C is the cumulative sum of the peak SPE events in each half-year based on Table 3. In this analysis, C is, therefore, proportional to the total fluence of the strongest SPE events. The proportionality constant depends on the integrated flux from each SPE event, and its solid angle. For this approximation, we assume that the SPEs have comparable durations (typically ~day) and effective solid angles at the spacecraft.

The best fit to the SOHO data (Figure 2 dashed line) was obtained for  $\alpha = 0.74$  and  $\beta = 16000$ . We note that this fit works best for the discrete 'Peak' events in Table 3 but is considerably worse for fits to the total fluxes each year. Apparently, there is a thresholding effect that favors only the strongest SPE events as the major causes of solar panel degradation. From the discrete event fit, we determine that, for the SOHO data, there is an annual cosmic ray decline of 1.5% and a conversion from SPE, pfu units to power loss of 16000 pfu per percent. Our simple model predicts that, as a consequence of the major SPE event on November 4, 2003, that the current SOHO power is at approximately 81% by December 2004.

We assume that the power loss rate is roughly linear with the SPE flux over the range from 16,000 to 31,000 pfu, and that this linearity can be extended over the range from 3,000 to 100,000 pfu, corresponding to a range of power loss per event of 0.3% to 6%. This allows us to estimate the current operating levels of the 367 working GEO satellites launched after 1976. To do this, we have simply determined for each satellite the number of years since launch to 2005, and multiplied by the power erosion rate of 2% per year to determine the amount of expected degradation. Based on the documented history of SPE events and their fluences since 1976 we have added to each satellite's cosmic ray power degradation, a contribution caused by known SPE events since launch.

We note that the SOHO fluxes are measured in interplanetary space, while the relevant GOES satellite fluxes at GEO should allow for partial shielding by Earth's magnetic field. It is known that the hardness of the particle spectrum is affected by location in the magnetosphere, and that SPE particles with energies above 10 MeV are the most damaging to satellite electronics and solar panels [e.g. *Lucci*, 2005]. GEO satellites are located at 6.6 Re where the spectral hardness change, compared to interplanetary space, is expected to be modest. In the models to follow, we will not attempt to correct for this affect at the present time.

Including both the cosmic ray and SPE effects, our model summarized in Figure 3 (lower curve) indicates that 26 of the 367 GEO satellites appear to be operating at below 50% of their beginning-of-life (BOL) power levels by 2005. There are few satellites older than 15 years in the current sample, and that as indicated in Table 4, there are no active Earth-orbiting research satellites or communications satellites older than 15 years. The preponderance of military systems among the oldest satellites may indicate a more robust satellite design, or simply that the actual state of functioning is poorly described in public documents.

The sharp drop in the number of old GEO satellites operating at what we would estimate as 30% of their BOL power suggests that this is a threshold below which most categories of GEO satellites are retired, replaced or otherwise become unusable.

An aggregate revenue loss due to SPEs can be estimated by using our average transponder base rate of about  $\$2 \times 10^6$  per year. This rate, when multiplied by the number of transponders on the satellite, and the years lost to SPEs, yields the satellite's lost income. We will also consider only satellites launched after 1990 that would be retiring in 2005, which corresponds to the canonical 15-year EOL horizon. If only the cosmic ray rate is responsible for satellite EOL, it will be assumed there is no loss of revenue since this factor was considered in the lifetime estimate and the satellite owner's profitability calculation. However, SPEs will advance the retirement date by an amount equal to their equivalent number of cosmic-ray years. For example, the SPE of July 14, 2000 presumably caused a 2% power loss for all satellites operating on that date. This equals a full year of lifetime loss at the expected 2% per year cosmic ray rate. For 20 transponders operating at  $\$2 \times 10^6$ /year this results in a  $\$4 \times 10^7$  loss of potential revenue if the

satellite is decommissioned after 14 years because of SPE events, rather than the baseline 15 years of normal operation based on cosmic ray degradation only.

We have calculated the revenue of the commercial GEO satellites through 2004 by subtracting the number of years lost due to cosmic rays and SPEs from the age of the satellite by the end of 2004. We multiply this difference by the number of transponders in each satellite, and by the transponder leasing price of  $\$2 \times 10^6$ /year. According to our database of working commercial GEO satellites, the 78 satellites (containing 1,860 transponders) launched in 1996 or earlier have a net revenue of  $\$6 \times 10^9$ . They continue to operate well past their expected EOLs, which averages about 12 years. The satellite that generated the most revenue is Intelsat-701 launched in 1993. By 2004 it has been operational for 11 years. During this time it has experienced about 7.8 years of lost operation due to SPEs and cosmic rays. Its 36 transponders have generated  $\$2.34 \times 10^8$  in revenue, and the satellite still has four years to go for its scheduled 15-year EOL. The additional 157 commercial satellites launched between 1997-2004 (inclusive) with an estimated 4,980 transponders have already experienced a loss of  $\$1.3 \times 10^{10}$  from SPEs. However, the oldest of these satellites is only 7 years old. The average planned lifetimes are 15 years, which means that they are only half way through their expected operating lives. What affect will SPE and cosmic ray degradation have on this population just before sunspot maximum in ca 2012?

By 2012, the cumulative age distribution of the satellites launched before 2005 shown in Figure 4 (upper curve) will include more than 160 satellites older than 15 years. If we assume a distribution of SPEs similar to what was experienced between 1993-2004, we can predict that by 2011, about 310 satellites of the existing 367 GEO satellites will be operating at less than 60% BOL power according to Figure 3 (upper curve), and 60 satellites will be operating below the imminent-replacement threshold of 30% BOL power. To offset this normal rate of satellite aging, approximately 160 replacement satellites will need to be launched between 2005-2012, which corresponds to an annual launch rate of about 22 satellites. This is similar to the forecasted launch rates between 2004-2010 estimated by COMSTAC [2004], suggesting that our baseline satellite model (sans a superstorm event) is consistent with current market forecasts for the commercial GEO satellite sector.

## 4.2 Single Event Upsets

Previous space weather events have also produced a wide array of on-orbit 'anomalies', although there seems to be no coherent model to explain why some satellites are affected while others of similar design are apparently not. For example, on January 11, 1997 the Telstar 401 communication satellite was disabled by a space weather event. This satellite uses the Lockheed Martin AS-7000 bus, which is also used on AsiaSat II, EchoStar III and Telstar 402. One reason might be orbital location at the time of the event. Satellites at midnight local time are more vulnerable than at other local times since the electrons reach GEO from the magnetospheric tail. Some of these events are caused by SPEs, while others are caused by energetic electrons  $>1$  MeV, which have been



referred to as ‘killer’ electrons by Baker [1997]. In either situation, these particles penetrate deep into the spacecraft and cause SEUs or other logic errors that can lead to corrupted data and phantom commands. They can also cause satellite charging where energetic electrons differentially charge various parts of satellite surfaces. When discharges occur between different surfaces, currents are induced in satellite wiring, sometimes causing problems. The most common is attitude control system problems due to signals induced on attitude sensor wiring.

*Lucci et al.* [2005] and *Mountford and Sastry* [2000] have done extensive studies of satellite anomalies. The former study involved anomaly data for 220 satellites between 1971 and 1994. The second study used the twelve SKYNET satellites and electrostatic discharge data between 1990-2001 correlated with Kp index and its first derivative, as a measure of environmental factors.

Assessing the impact to this resource from a superstorm requires us to show that such storms are qualitatively very different in scope from the storms we have already encountered since the start of the space age. If a superstorm is only incrementally different than the storms we have already experienced, it is unlikely that the impact to satellites will be anything more than incremental as well. Of course, we can not discount the possibility that the impacts may enter a non-linear regime so that a factor-of-two increase beyond recent storm levels we have experienced will generate more than a factor of two increase in satellite problems. There is reason to expect that such non-linearities between fluence and SEU frequency may be important. For instance, the number of secondary particles generated by SPEs depends on the satellite shielding – essentially the satellite’s mass [*Panasyuk*, 2001]. One may expect that heavier satellites have a larger ‘non-linear’ problem with SEUs produced by secondary particles, than lower-mass satellites. Also, according to models by *Belov et al.* [2004] the relationship between proton flux and satellite anomalies is a power law, rather than a linear relationship.

### 4.3 Orbit Decay

Satellite orbit decay is a complicated function of the mass-to-surface-area cross-section in the direction of travel ratio of a satellite, and the atmospheric density profile, – quantities that are not easily determinable for each of our database members. Increased solar UV increases the heating of the atmosphere and increases its density. Figure 5 shows the impact that changes in atmospheric solar heating have had on the frequency of satellite re-entries since 1967, based on data from *Space Track* [2005]. A clear correlation is evident in which the largest numbers of re-entries occur during the peak years of sunspot cycles in 1968, 1979, 1989 and 2000.

Although the time scale for these solar cycle variations is on the order of several months, individual space weather events lasting less than a day also take their toll on satellite perigees. This can be seen in the altitude log of the International

Space Station during the Bastille Day, 2001 storm as described by *Hammons* [2001] and shown in Figure 9.

## 5.0 Historic Superstorms

The study of space weather superstorms has increased over the last few years, primarily because we have not encountered such an event since our satellite network reached its current level of sophistication. Despite considerable recent speculation, it is not known how extensive the impact from an actual superstorm might be. Informal opinions seem to run the gamut from 'all satellites lost' to 'minimal impact'.

The study of the record of historic SPE events during the last 500 years by *McCracken et al.* [2001a, b] reveals over 125 such events that have left their traces in the nitrite abundances of polar ice cores from Antarctica, Greenland and the Arctic Region. The strongest of these coincided with the 1859 Carrington-Hodgson storm and white-light flare. A historical study by *Cliver and Svalgaard* [2004] of the major storms since 1859 reveals a rather broad ranking of these events across the many physical parameters that characterize these events. Table 5 shows the four historical storms that achieved the most extreme values for the indicated parameters: CME speed, SPE proton flux, Dst, Sudden Ionospheric Disturbance (SID) recorded on a magnetogram, minimum magnetic latitude and flare luminosity. Of these, the Carrington-Hodgson 1859 storm appears as the most extreme event in nearly all categories.

The 1859 Carrington-Hodgson superstorm produced the largest SPE from the ice core record with an equivalent fluence of  $18.8 \times 10^9$  particles/cm<sup>2</sup>. Similar results have been reported by *Townsend et al.* [2003, 2004] and have led to predictions of severe astronaut radiation exposures leading to acute sickness even within well-shielded spacecraft (Shuttle). The July 14, 2000 Bastille Day SPE had a fluence of  $6.3 \times 10^9$  particles/cm<sup>2</sup> for protons with  $E > 30$  MeV, and was observed to cause a 2% power decline in the SOHO satellite. This translates into a Carrington-Hodgson equivalent power loss scaled from the SOHO data of  $(18.8/6.3) \times 2\% = 6\%$ . Is this the worst-case?

*McCracken et al.* [2001] have identified the solar activity cycles during the satellite era as being uncharacteristically weak in SPE events and fluences compared to the historical record of these events since the year 1567. The frequency of large events with  $> 30$  MeV fluences  $> 2 \times 10^9$  particles/cm<sup>2</sup> between 1964-1996 averages one event per sunspot cycle, while 6 – 8 such events occurred for sunspot cycles near the years 1605 and 1893. The integrated fluence of the largest five SPEs between 1830-1910 was  $54.9 \times 10^9$  particles/cm<sup>2</sup> compared with only  $6.7 \times 10^9$  particles/cm<sup>2</sup> during the years 1910 to 1985. In particular, the satellite era (1967-1994) ranks sixth lowest in the integrated fluences of the strongest 6-8 SPEs. The implication is that, during the last 400 years, the sun is most certainly capable of producing a substantially more active satellite environment than what we have come to accept in recent

decades. Depending on the assumptions made about the spectral hardness of the Carrington-Hodgson event, the fluence for  $>30$  MeV protons may have reached levels near  $36 \times 10^9$  particles/cm<sup>2</sup>; a factor of two greater than assumed in the above discussion for power loss (i.e. 12%).

Reedy [1998] examined isotopic abundances in lunar rock surface layers to estimate the SPE fluence distributions for the last few million years. Apparently, the upper limits suggest that there have been no flares with fluences more than resulted from 10-times the average of flares seen during the last few decades. The 1859 flare is only 3-times more luminous than flares seen in recent decades. This suggests that the distribution of SPE fluences has a sharp turnover at levels just above the 1859-level. We can then assume that a storm more than 3 times as intense as the 1859 event is a reasonable upper limit 'worst case' event. This means the brightest SPE may have a flux of about  $(18.8 \times 3) = 56 \times 10^9$  particles/cm<sup>2</sup>, resulting in a power reduction of 18%. Once again, these events averaged over several million years are substantially less common than the 1859 event. Nevertheless, they represent an upper limit on the true worst case superstorm event, and so we will use this flux, and the corresponding 18% power decline that results, as an upper bound to what we could reasonably expect from a single event.

At what time during a solar activity cycle might we expect such major storms to occur? Table 6 shows the years for the 10 largest SPEs recorded since 1976 compared to the year of sunspot maximum. Although the sample of large SPE events is statistically small, apparently, the largest storms occur within 2 years after sunspot maximum, with no major storms occurring in the two years prior to sunspot maximum. In the models to follow, we will consider the worst-case scenario for a superstorm, precipitating an 18% decline in solar panel power, occurs at the time of sunspot maximum in the year 2012.

## **5.1 GEO satellite systems**

### **5.1.1 Solar Panel Degradation**

Previously in Section 4.1, we used our satellite database, together with the estimated power degradation from the historical SPE events since 1976, and cosmic ray degradation, to determine the current 2005 solar power operating levels. The most recent satellite launches in this database occurred in 2004, so in the discussions to follow, we extended our satellite operational model to 20 years beyond this last launch year. This represents the far-horizon on anticipated satellite retirements from the current fleet based on industry expectations for satellite systems built in the early 2000's.

Model 1 – Prior to the superstorm in the year 2012, our baseline model described in Section 4.1 suggests 60 satellites would normally be operating below the 30% threshold. The addition of the superstorm in 2012 brings the total to 152 satellites that would fall below the 30% limit after the event, and requiring immediate

replacement. The superstorm causes a prompt loss of 92 additional satellites below the 30% threshold for 2012. What is more interesting, however, is the future run-out of this event through the year 2024.

If we assume a distribution of SPEs similar to the 12-year period from 1992 to 2004, the baseline model suggests that 280 of the 367 satellites would require replacement under normal SPE and cosmic ray conditions. With the superstorm, all of the 367 satellites require replacement. This means  $(367 - 280 =) 87$  satellites launched after ca 2002 were affected by the superstorm and had to be prematurely retired at power levels below 30%. The replacement cost for these 87 satellites is  $\$2.4 \times 10^{10}$ .

Comparing the predicted retirement years for the satellites before and after the storm, we estimate 1,575 years of lost service for this affected population. The total number of lost transponder-years is  $\sim 22,000$  resulting in  $\$4.4 \times 10^{10}$  in lost services. This service revenue loss would be in addition to the  $\$2.4 \times 10^{10}$  replacement cost for the additional 87 satellites affected through 2024, implying a total hardware plus service revenue loss of about  $\$6.8 \times 10^{10}$  through 2024 as a direct result of the superstorm.

A shortcoming of this model is that it does not include satellite launches after 2005. A portion of these future launches are slated to increase the capacity of the GEO satellite network to maximize service and profits. However, a second goal is to replace satellites to make room for newer-generation models with increased sophistication and capacity. We will now investigate the effect a superstorm has when satellites are replaced on a fixed 15-year schedule, which is the typical timescale quoted by industrial records for satellites launched since 1995.

**Model 2** - This is similar to Model 1 except that we first replace all of the communication satellites older than the canonical 15 year limit after 2004. We do this by simply adding 15 years to the launch year of each satellite prior to 2005 to determine the replacement year, and then re-set the solar power levels of the new satellite to 100% as the satellite's replacement is put into service. This results in no net growth to the GEO population between 2005-2024. As a consequence, by 2024 the 367 GEO satellites would have experienced 100% replacement, and the new suite of satellites would range from 50% to 100% operating solar power, with satellites launched before 1990 being replaced twice. For example, Intelsat 604 was launched in 1990. It would be replaced in 2005 with a new satellite, and that satellite would in turn be replaced in 2020.

Satellites operating through the modeled storm year 2012 would be replaced 'just in time' by the time their power levels reach about 40% so that no actual loss of service would occur. Satellites that would be replaced after the storm years would be unaffected. For this reason, we estimate that a worst-case superstorm near sunspot maximum would have little affect on satellite economic profitability so long as this 15-year replacement schedule is strictly adhered to. However, Figure 6 shows that this replacement rate would be relatively expensive to implement because it would involve in some years far more satellite launches

than we have experienced in previous years. This is especially true in ca 2015 and 2019 when we estimate ~40 satellites will need replacement. The sudden decline after 2020 is due to the retirement of satellites launched after 2005 and is outside the scope of this paper.

Comparing these two models, the estimated losses from a superstorm when no GEO satellite replacement occurs would be about  $\$6.9 \times 10^{10}$  in lost satellites and transponder revenue in the years following the event through 2024. The superstorm also would result in the premature replacement of about 140 satellites before their planned dates. Approximately 30 to 40 satellites would be operating below the 30% power level immediately following the superstorm. At the time of replacement, and following a superstorm event in 2012, the oldest satellites are operating at about 40% of their initial power, which is above the threshold described in Section 4.1. It appears that, when satellites are replaced according to a fixed 15-year schedule, the economic impacts of the superstorm are largely mitigated so far as solar panel degradation is concerned.

### 5.1.2 Killer Electrons and Satellite Anomalies

In addition to solar panel degradation, GEO satellites are often victims of energetic particle showers (e.g. killer electrons) that lead to a variety of electrical systems and commanding disruptions by SEUs. This phenomenon has been exhaustively studied from the engineering standpoint, but also from case studies of known space weather events and their satellite impacts by Baker [1997].

Belov *et al.* [2004] have studied the statistics for 6000 anomalies occurring among 300 satellites in various orbital regions, and found no correlation between MeV proton fluences and anomalies for satellites in LEO. However, they found increasing correlations for MEO-type satellite orbits, and the highest correlations for GEO orbits. The distribution of anomalies between 1972 and 1994 had occasional peaks of 0.10 and 0.13 anomalies per day per spacecraft. From this, they were able to construct models predicting the number of anomalies for each satellite population as a function of proton and electron fluxes. For GEO satellites they obtained:

$$F (10^{-4} \text{ anomalies/day/satellite}) = -54 + 1.4 \times 10^{-9} \times E_2^{1.2} + 0.83 A_p + 0.19 V - 0.15 B_z + 1.1 P_{100}^{0.35} + 1.6 P_{60}^{0.75} + 20 S_f + 1.5 da10$$

Where  $E_2$  is the >2MeV electron fluence in units of electrons/day/cm<sup>2</sup>/str averaged over the past 3 days from GOES;  $A_p$  is in units of nT averaged over the previous 4 days;  $B_z$  is the northward component of the interplanetary magnetic field in nT averaged over the previous 2 days;  $V$  = solar wind speed in km/sec averaged over the previous 2 days;  $P_{100}$  is the fluence of > 100 MeV protons in protons/day/cm<sup>2</sup>/str from GOES;  $P_{60}$  is the daily averaged GOES proton flux

above 60 MeV in protons/cm<sup>2</sup>/sec/str;  $S_f$  is the seasonal factor (1 at the solstices, 3 at the equinoxes), and  $da10$  is in units of % and measures the cosmic ray intensity [e.g. *Belov*, 1999].

From the NOAA [2005] archive for the GOES satellite, the October 29, 2003 SPE resulted in  $P(E > 10 \text{ MeV}) = 7.7 \times 10^8$  protons/cm<sup>2</sup>/day/str and  $P_{100} = 5.2 \times 10^6$  protons/day/cm<sup>2</sup>/str and  $E_2 = 1.9 \times 10^7$  electrons/cm<sup>2</sup>/day/str. The estimated  $P_{60}$  would be  $\sim 10^8$  protons/cm<sup>2</sup>/day/str or for an hour-long maximum phase,  $\sim 30,000$  protons/cm<sup>2</sup>/sec/str. This yields about 0.5 anomalies per satellite per day.

For the superstorm SPE with a one-hour duration of its main phase, producing a fluence of  $56 \times 10^9$  particles/cm<sup>2</sup> over  $4\pi$  steradians, we estimate  $P_{60} \sim 10^6$  protons/cm<sup>2</sup>/sec/str. We also assume a spectrum similar to the October 29, 2003 event for which  $P_{100} \sim E_2 \sim 0.01P_{60}$  so that  $P_{100} = E_2 = 10^9$  particles/cm<sup>2</sup>/day/str. Plausible ranges for the quantities,  $V(\text{km/s}) = (2500, 3500)$ ,  $B_z(\text{nT}) = (-100, -200)$ ,  $A_p(\text{nT}) = (10, 100)$ ,  $S_f = 3$  at the equinox, and  $Da10(\%) = (20, 100)$ , yield contributions to the total anomaly rate which are of the order 0.005 anomalies/day/satellite for their maximal values, compared to the much larger contributions by the fluence terms,  $E_2$ ,  $P_{60}$  and  $P_{100}$ , during a superstorm event. With these assumptions, the estimated anomaly rate  $F \sim 10$  anomalies/day/satellite. The model suggests that a superstorm event could produce an anomaly rate  $\sim 50$ -100 times higher than seen in the 1972-1994 historical satellite anomaly records thus far.

The relationship between anomalies and SEUs is not given in the analysis by *Belov et al.* [2004], so one might conclude that SEU rates could actually be much higher than the 'malfunction' rates cited by *Belov et al.* [2004]. There is some evidence for this elsewhere. For example, according to *Brekke* [2004], during the July 14, 2000 SPE event, the SOHO satellite's 2 gigabyte memory encountered 76 SEUs per minute or an equivalent of 109,000 SEUs per day. The flux of that event was 24,000 particles/cm<sup>2</sup>/sec. By extrapolation, the 1859 superstorm with a flux three times greater could have nearly 228 SEUs per minute or 328,000 per satellite day. Only some of these might generate an actual satellite anomaly event. The SEU production of, for example, 100 additional false-stars in a CCD image used by the attitude control system (ACS) might yield only one actual anomaly of a satellite mispointing. The ASCA satellite was lost due to ACS anomalies caused by SEUs according to *Space News* [2002]. However, the issue for satellite operators is, what will the managing of satellite operations be like when the SEU event rates become thousands of times higher than conditions they have witnessed thus far in anomaly management?

If we scaled our operating fleet of 936 satellites to Belov's normal satellite anomaly rates, we might expect to experience about  $(0.13/\text{satellite}/\text{day} \times 936 \text{ satellites}) \sim 120$  anomalies per day across the entire existing fleet of satellites. During the superstorm, the worst-case fluences suggest anomaly rates at least 50 times higher (several per day per satellite). At rates of about  $(120 \times 50 = )$  6000 anomalies per day for an entire fleet of satellites, is it likely that the conditions for unrecoverable anomalies can be met? A study by *Robertson and Stoneking* [2003] of the specific systems affected by mission-critical, anomalies shows some troubling trends.

Between 1990 and 2001, 128 mission-critical anomalies were identified in the survey during the design life (not the extended life) of 764 satellites. Scaling this study by the number of satellite anomalies investigated by Belov (e.g. 6,000) among 300 satellites during 1971-1994 (23 years) we might expect  $(11/23 \times 6000) = 2,900$  anomalies during the 1990-2001 period, of which 128 or 4% are mission-critical. Translating this to the estimated superstorm anomaly rate for the entire 936-satellite constellation of 6,000 per day, we estimate that there might be of the order of 240 mission-critical anomalies brought on by a superstorm. The most intense phase of SPE events generally last only a few hours, so this clearly suggests that satellite failure mitigation by ground controllers will be a challenging battle.

The most common mission-critical, anomalies (40%) involve the ACS (specifically the momentum wheel), and the electrical power system (solar panels and batteries) which *Robertson and Stoneking* [2003] identify as resulting in 13 of the 43 total satellite losses (30%) among 10 possible categories. Assuming that the 128 anomalies were distributed randomly across the sample of 764 satellites during the 1990-2001 period, most of the mission-critical, superstorm anomalies would also involve ACS and EPS systems, and we might expect of the order of  $(43/128 \times 240) = 80$  satellite failures from this one event, of which 30% would involve ACS and EPS failures.

## 5.2 MEO Satellites

The 132 working MEO satellites include the US Global Positioning System and the Russian GLobal Navigation Satellite System (GLONASS), which collectively constitute over 58 satellites, in addition to 49 additional military communications and research satellites. The GPS system is, by far, the most critical of these MEO systems. As a result of the de-classification of this technology and its rapid integration into a growing suite of civilian consumer items, it is estimated that there are 100 times more civilian users of GPS data than military consumers, and this market is rapidly expanding. By 2008 it is anticipated that revenues from GPS technology and consumer goods will exceed  $\$2.2 \times 10^{10}$ , with over  $8 \times 10^6$  vehicles equipped with GPS systems worldwide [GPS World, 2004]. In 2008, a European satellite network called Galileo is scheduled to join GPS and GLONASS as a new civilian global positioning system.

The completed GPS constellation has 24 spacecraft in 6 high-altitude orbit planes in addition to 5 spares, each with a 7.5 year lifespan for Block IIA satellites launched from 1990 to 1996. By 2005, all of these satellites are older than their planned lifetimes. Many of the 19, Block 2A satellites launched between 1990 and 1996 are still operational at ages of 12-14 years. The 13 Block IIR satellites launched between 1997 and 2004 are only now reaching their estimated EOLs, though they are expected to exceed this by a large margin as for Block IIA. Up to 12 Block IIR replacement satellites (called Block IIRM) were to be modified to use the new military M-code and are to be launched between 2005 and 2006, with initial operational capability by 2008 and full capability by 2010 [*Global Defense*, 2001]. Improvements in the Block IIF over previous satellites include a design life of 12.7 years and a dramatic increase in the growth for additional payloads and missions [*GPS Fact Sheet*, 2000]. The first of an estimated 12 Block IIF launches will start in 2007 [*Guenthers Space Page*, 2005].

Because age seems more verifiable in military satellite operations than predicted power level or the satellite's response to power erosion, we will examine the age distributions of the US GPS satellites and assume a replacement of services (by backup spare or new satellite) happens after 15 years. We also assume from the 18% power degradation estimate for a superstorm, that a satellite would age  $18/5 \sim 4$  years. This rate is lower than for communications satellites because the GPS satellites survive for nearly as long as GEO communications satellites even though the solar power decline rates in MEO are 5% per year according to *Patel* [2000], rather than 2% for GEO satellites according to *Chetty* [1991].

Model 3 – The model begins in 2004 when 11 of the 29 GPS satellites are already past their nominal 8-year lifetimes. The older models are being replaced at the rate of 3 per year (ca 2003 and 2004), so by 2008 the entire Block IIA will be replaced by 12 newer models – the Block IIRMs. GLONASS, meanwhile, has 10 operational satellites in 2005 with a goal of restoring the full 24 by 2007. The European Galileo GPS system will have 30 operational satellites by 2008.

By the time of an assumed superstorm in 2012, all 12 of the Block II-RM satellites would reach or exceed their 12-year replacement lifetime. The number of operating satellites will probably be lower than the 24 needed to maintain a fully operational GPS system, spanning all geographic locations, and available at all times at the designed accuracy. The GPS constellation will consist of satellites operating well beyond their predicted replacement lifetimes following the Superstorm. Without replacements, it seems unlikely that the constellation would be able to provide the minimum of four satellites for ground-level GPS positioning at the designed accuracy, especially for military and aviation applications.

The relatively youthful Galileo system also would fare rather poorly for launches between 2006-2008. Galileo satellite ages in 2012 would be between 4-6 years. Following the superstorm, this would rise to 8-10 years which is near the planned life expectancy for this system. The new GLONASS satellites launched between



2005-2007, with their intrinsically short lifespans of about 7 years would most likely be eliminated from operational status by a superstorm in 2012.

In addition to the premature retirement of some of the GPS satellites, and possibly the failure of the system to operate with a full satellite complement, the accuracy of the GPS system would be impaired regardless of whether satellites are lost or not.

Differential GPS (DGPS) measurements available to the more expensive ground-based navigation systems (military, marine, air navigation) are less sensitive to ionosphere disturbances, however they are not completely immune from large gradients in ionospheric total electron content (TEC) according to studies by *Skone et al.* [2004]. During the October 2003 storm, the DGPS errors reached 20 meters, compared to quiet-time conditions of only 1-2 meters. [GPSworld, 2004]. During the Bastille Day-2001 storm, horizontal position errors of 20 to 40 meters were recorded for several hours using DGPS [Skone et al., 2004]. These position errors exceed the 5-10 meter limits for maritime navigation, and greatly exceed the 2-5 meter position errors for aviation and military applications.

During the superstorm, severe ionospheric and geomagnetic disturbances could be expected to prevail for 24-72 hours based on the durations of historical storms, causing GPS users to have severely degraded positions for extended periods of time. The magnitude and duration of such a storm would, doubtless, have large practical impacts to airlines, military, and rescue services worldwide. There will also be 10s of  $10^6$  of automobiles and other civilian position-finding systems in place by 2010 for which 50 to 100-meter errors will render city driving by GPS useless, or even hazardous.

## 5.3 LEO satellites

### 5.3.1 Orbital Decay

As of 2004, there are 437 satellites in LEO that appear to be still in operation. These satellites are primarily communication systems (e.g. Iridium, Globalstar), Earth resource mapping (e.g. Landsat-7), and imaging systems (e.g. Spot-5) that require LEO for the best mission outcomes. Many astronomical research satellites and manned platforms (e.g. Hubble Space Telescope and ISS) are in LEO. Figure 7 shows the population distribution with perigees less than 1400 km. The large change near 600 km represents the members of the Iridium satellite constellation. Although LEO satellites are considerably less vulnerable to SPE and solar panel degradation, their largest risks come from atmospheric friction and orbit decay. These conditions are known to change markedly during the solar cycle.

Although the detailed re-entry behavior of LEO satellites depends on their individual aerodynamic properties, calculations of orbit decay times for reasonable satellite geometries and masses suggests that at altitudes of 300 km, decay times under normal atmospheric conditions, and without preventive

measures, are of the order of a week. At 150 km, the de-orbit time is a day or less. Satellites below 300 km appear to be at highest jeopardy, especially those with perigees near 100 km. Some satellites are able to re-boost themselves, however it is not known which specific systems have this capability, or how much propellant remains at the present time to carry out this function beyond 2005. Let's consider three cases of satellites that are not re-boosted:

Hubble Space Telescope. According to the HST Status Report [*SpaceRef*, 2003], the worst case scenario has no re-boosting after 2003, and a moderate solar cycle peaking in 2012. The 11,000-kg, HST begins in 2003.5 with an orbit altitude of about 575 km, which remains largely unchanged until 2009.5, then begins a rapid decrease to 500 km in 2011.5, 450 km by 2012.5 and then re-enters at 200 km by 2016.0. Total remaining time in orbit since 2003 at an initial altitude of 575 km is about 12.5 years.

Starshine. According to *Science@NASA* [2001], this 80-kg satellite began with an initial orbit perigee after sunspot maximum (Starshine-3), of 475 km in 2001 and re-entered in 2003.

SNOE. Launched in February 1998 into an orbit with a 580 km perigee, this 115-kg satellite reentered in January 2004.

ASCA. This 417-kg satellite was launched in 1993 into an orbit with an initial perigee of 570 km, and re-entered in 2001.

Model 4 – A simple model for orbit decay was created and applied to the LEO satellites, based on the formula:

$$P(t) = P_0 - A t^\alpha$$

where,  $P_0$  is the initial orbit perigee, and  $A$  and  $\alpha$  are constants that have been fitted to representative orbit decay plots for a small selection of satellites between 400 to 600 km. Satellites above 600 km are assumed to have orbit lifetimes longer than 25 years, even during solar maximum conditions, with only modest perigee changes of 1 km/yr. Below 600 km, our simple function,  $P(t)$ , is assumed to take affect until altitudes of 300 km are reached, at which point un-boosted satellites have only a few weeks of remaining lifetime.

The fitting constants are shown in Table 7 for solar maximum and solar minimum conditions. A representative fit for the SNOE de-orbit is shown in Figure 7 (dashed line). Although the range in mass for the satellites is a factor of 7000, the fitting coefficients fall in a very narrow range, with mean values of  $A = 0.6 \pm 0.3$  and  $\alpha = 0.4 \pm 0.2$  during solar minimum and  $A = 1.3 \pm 0.2$  and  $\alpha = 0.4 \pm 0.2$  during solar maximum. Although the value of the constant  $A$  depends on solar cycle phase, the power-law index shows little solar cycle variation.

We have fitted a simple sinusoid with a period of 11 years to the constant A to determine an analytic formula for the solar cycle contribution, and obtained the following form:

$$A(t) = 0.9 + 0.6\cos(0.57(t-t_0))$$

where  $t_0$  is the sunspot minimum year 1996. The best-fit satellite decay function is therefore:

$$P(t-t_{\text{launch}}) = P_0 - (0.9 + 0.6 \cos(0.57(t-1996))) (t - t_{\text{launch}})^{0.4}$$

With this albeit simple analytic decay formula, which does not allow for cycle-to-cycle variations in solar activity, we have determined the perigee evolution of the 437 LEO satellites below 600 km at launch, and through the year 2024. In order to establish the population baseline for this model we do not include the effect of a superstorm in 2012.

We were able to obtain the launch dates and initial perigees for 422 satellites, of which 393 have apparently survived to 2004. The distribution of these satellites with perigee is shown in Figure 8 (dashed line). According to our orbital decay model, the remaining 29 non-surviving satellites were launched before 1996 and include only four civilian satellites (Hubble Space Telescope, BeppoSAX, SAMPEX, XTE). Because of the extreme ages of these operational satellites and their low initial perigees (500 km – 130 km), they are no doubt being actively maintained in orbit against orbital decay.

A superstorm event would be expected to temporarily increase the atmospheric drag for the lower-altitude LEO satellites, thereby reducing their perigees. The amount of perigee reduction depends on the details of the upper atmospheric storm heating, and could plausibly range from as little as a few kilometers at altitudes near 600 km, to perhaps as much as 20 km or more at ISS altitudes of 350 km. For example, the orbital perigee of the ISS was reduced by 15 kilometers within a few hours during the Bastille Day storm on July 14, 2001 [Hammons, 2001]. We have examined the impact of such a transient event by adding to the LEO baseline model a 60-kilometers orbit decrease in 2012 to all surviving satellites below 700 km. There appear to be two components to this impact, one prompt and the other delayed.

Our simple orbit decay model suggests that only a very small number of satellites in the existing population (for example Swift, Icesat, Ziyuan 2-3, and Trace) would be close enough to the 300-km threshold in 2012 for imminent re-entry following the superstorm. For example, the 1,500-kg Swift satellite was launched in 2004 into an orbit with an initial perigee of 600-km on a 2-year mission to study gamma-ray bursts. Were it to decay in a manner similar to the SNOE satellite [SNOE Team, 2004], Swift could reach an altitude of 380 km by 2012. An additional 60-km altitude reduction would place it at 320-km in the regime for

rapid re-entry within a few weeks. This essentially accelerates its de-orbit time by a full year, similar to the unplanned re-entry of Skylab in 1979.

Looking farther into the future, however, the superstorm event causes the accelerated decay of all satellites below 700 km, and results in a second wave of re-entries by 2021 (long after the planned de-orbiting of the ISS) involving 98 satellites. These satellites were at altitudes above 600-km just before the superstorm and should have remained in orbit for several decades. The total replacement cost of these satellites is  $\$1.6 \times 10^{10}$ . The most notable members of this population are the entire ORBCOMM network, 20 communications satellites, the Ikonos, Landsat and SPOT imaging satellites, and research satellites such as Terra, Aqua, TIMED and GP-B. The most expensive satellite in jeopardy seems to be the  $\$3.1 \times 10^9$ , Helios-2A. Of course, the average age of these systems by 2021 will be in excess of 20 years so it is plausible to assume that they will be retired and replaced long before the model suggests their orbits will decay. Also, at the time of the modeled superstorm, the average ages of the satellites will be ~10 years. Since an unknown number of these satellites have automatic station-keeping systems that mitigate against orbit decay, they are still young enough that these systems may still have the capacity to obviate the worst effects of such a storm, though at a considerable cost to their fuel reserves.

Although the small number of LEO satellites immediately affected by the storm makes this analysis appear reassuring, the greatest practical concern actually relates to the International Space Station. Depending on the details of the atmospheric heating from a superstorm, the ISS perigee decay may well be near-catastrophic. It is currently scheduled for retirement sometime after 2014, so it would be operating during our model superstorm year.

The altitude history of the ISS from 1998-2005 [NASA, 2005] in Figure 9 shows the periodic 'saw-tooth' re-boosts needed to maintain its orbit between 340 - 400 km. During 2005, the ISS perigee is expected to decline about 90 meters per day and requires re-boosts every 10 to 45 days [JSC, 2002]. During the 2000 solar maximum, the decay rate was much higher: 400 meters per day. Without frequent correction, the orbit would decay within about two years. Re-boosts are currently provided by either the US Space Shuttle [about 40 km altitude per event e.g. *Science@NASA*, 2000] or by the Russian Progress vehicle [3 km altitude per event e.g. *SpaceToday.com*, 2005]. The ISS will eventually have its own propulsion system, but there is as yet no firm schedule for its completion. Estimates for the maximum perigee change by *Messerschmid and Bertrand* [1999] suggest that 40 m/sec is the maximum capacity for the Service Module, which translates into approximately 70 kilometers of altitude change at 425 km. If a superstorm event should happen to arrive just before the scheduled re-boost in 2012 at sunspot maximum, the additional storm-related perturbation combined with the anticipated decline in altitude, could easily be outside the capacity of the SM or the Space Shuttle. There is also a second hazard that could be exacerbated by a large storm event, namely, collisions with prematurely re-entering satellites.

In 2003, the ISS had to be moved to avoid a near-collision with the Italian satellite MegSat 0 which, otherwise, would have entered the 4 – 50 km 'zone of avoidance' surrounding ISS. This, however, was the sixth time such a satellite avoidance maneuver had been performed by the ISS. All satellites with orbits just above the ISS are carefully watched to avoid such incursions, however, a superstorm could easily create a new population of ISS collision threats over the course of only a few hours. The ISS orbits within a range of altitudes from 320 km to 400 km, so likely threats could come from satellites with orbits between 320 km to 500 km by 2012. In order for a satellite to enter this zone following a superstorm event in 2012, it would need to have a perigee in ca 2004 near 600 km. Only the SciSat-1, Swift and Icesat satellites launched in 2003-2004 are viable candidates. This means that the potential threats to ISS may not have been launched by 2004. The shaded entries in Table 8 have estimated re-entries within a few years prior to 2012, and may also be possible candidates. However, Table 8 also includes an unknown number of satellites that are capable of re-boosting, and are therefore not likely to be relevant to such an analysis.

### 5.3.2 Radiation Effects

Although not specifically investigated in the current paper, astronaut radiation effects from a superstorm event are also of considerable concern. Recent studies by *Townsend et al.* [2004, 2005] and *Stephens et al.* [2004] have utilized the data by *McCracken et al.* [2001] to determine the radiation dosages from a Carrington-type event, assuming spectral hardnesses similar to the August 1972 SPE. The consequences depend rather sensitively on the assumed spectral hardness for proton fluences at >30 MeV, however, shielding and radiation dosage calculations suggest such superstorm events are likely to be survivable by astronauts and spacecraft systems.

For astronauts and spacecraft in LEO or ISS-type orbits that do not spend significant time in the polar regions, spacesuited astronauts (1 gm/cm<sup>2</sup> aluminum shielding) would receive 1.4 Grays or 140 Rads) which would likely result in nausea, malaise and some damage to blood cells. Inside a spacecraft (< 10 gm/cm<sup>2</sup> aluminum shielding) a blood forming organ (BFO) dosage of no more than 0.7 Grays (or 70 Rads) would result, with no acute radiation damage. In the case of electrical systems, shielding of 0.1 gm/cm<sup>2</sup> yields 13.6 kiloRads, while 5 gm/cm<sup>2</sup> yields 0.9 kiloRads. These dosages are well within operational limits for most satellite electronics. These limits are substantially exceeded, and near-lethality conditions are reached, if the SPE at the estimated strength of the Carrington fluence has a spectrum similar to the September 1989 or March 1991 events, which are predicted to have yielded satellite radiation dosages exceeding 25 kiloRads according to models by *Townsend et al.* [2003].

Meanwhile, for interplanetary travel outside the magnetosphere and atmosphere, crew radiation dosages assuming a spectral hardness similar to the September 1989 SPE yield severe radiation effects including in some shielding scenarios, even crew fatalities.

According to the data assembled by *Townsend et al.* [2005], there is only a very weak trend to suggest that the hardness of the strongest SPEs are correlated with their intensity. For this reason, it is not possible to accurately anticipate whether a superstorm SPE would be a minor nuisance (soft spectrum) or a potentially catastrophic condition (hard spectrum). However, in considering the worst-case scenario for safety reasons, it may be prudent to assume that more shielding is better than less, and that the risk to humans and satellite electronics as presently deployed is worth taking seriously.

## 6.0 Superstorm Consequences

### 6.1 Favorable Considerations

Satellites are incredibly hardy. Perhaps the best indication we have to suggest our satellite resource is a robust one, is that we have currently experienced nearly a dozen major space weather events since 1980, with no widespread loss of satellite resources. Satellites appear to have evolved into highly resistant systems that seem able to survive the significant storms of the last 20 years, with fluences nearly as large as the 1859 Superstorm. The fact that there are at least a dozen different satellite designs now in operation may also be a large part of the reason why space weather events have not had a more widespread damaging effect.

We have more transponders than are currently in use. Mitigating factors to transponder/satellite loss include transponder overcapacity and the vast improvements in satellite technology. Currently, there is a nearly 50% overcapacity in unused transponders according to *Futron* [2003], allowing many GEO satellites to operate at undercapacity.

It is possible to mitigate many SEU effects by using software. Commercial 'off-the-shelf' processors that run sophisticated error-detection software have demonstrated the potential to reduce SEU events and their impacts to very low levels. NASA is exploring new technologies such as the Environmentally Adaptive Fault Tolerant Computing System to be flown on the ST-9 spacecraft in about 2010, which will detect and eliminate the effects of SEUs. This will reduce the need for radiation-hardened processors, and have a significant impact upon the reliability of commercial satellite systems during solar storm events.

There are specific ways to protect satellites from storm damage. Satellites can be put in 'safe' configurations where solar panels present the smallest cross section to the sun. This will inevitably mean a total loss of satellite function for up to several days before the event, and at a large economic cost. Even so, the October 2003 storm produced many severe satellite problems among systems that were presumably 'safed' in one way or another but this defensive action did not eliminate satellite problems entirely. For example, satellite controllers at Inmarsat were able to quickly react to activity to control their fleet of nine geosynchronous satellites. According to *Webb and Allen* [2004], two satellites

experienced speed increases in momentum wheels requiring firing of thrusters, and one had an outage when its CPU tripped out.

In time, GPS replacement satellites may become invulnerable to errors. The GPS system has rapidly become a major military and economic asset, depended upon by millions of military and civilian users. Although the current funding difficulties for this system may delay the installation of the GPS Block IIM, IIF and III systems, it seems unlikely for security reasons alone that this system will be placed at risk. There are, currently, a dozen backup satellites on the ground, and four deactivated as reserves on-orbit. Moreover, they have an impressive history of weathering the space environment in the midst of the Van Allen Radiation Belts for lifetimes exceeding 10 years in many cases. A Superstorm event may not be enough to 'take down' this system, but it may produce unprecedented ionospheric disturbances and the temporary filling-in of the slot region itself, affecting position errors globally. A mitigating factor is that the Block IIF satellites, when operational, will have a civilian 'L5' channel that has been added to provide Total Electron Content (TEC) information directly. In principle, this will be used to automatically correct the individual satellite signals for ionospheric disruption. The effect of a superstorm event on position errors may be entirely eliminated by this means.

## 6.2 Unfavorable Consequences

Even under the best of scenarios, satellite operators will be swamped with problems. A survey of satellite engineers and operators by *Futron* [2003] finds that satellite operators spend 40% of their time working with satellite anomalies. Because a single company may have more than one type of satellite in operation, and multiple types of spacecraft buses (e.g. PanAmSat has five different types of satellite buses) the logistics of managing satellite anomalies has recently become complicated. Our estimates for a substantial increase, by several orders of magnitude, for satellite anomalies all occurring during a superstorm would be a major hardship for satellite engineers and operators, and may well exceed their abilities to monitor, anticipate and correct severe malfunctions before they became fatal to the satellite. The ASCA satellite was lost because ISAS could not react fast enough to the changing space weather conditions affecting the satellite. The ebb and flow of the storm conditions will undoubtedly be very complex in time, forcing operators to experience intense periods of activity and intervention. The statistics of the large numbers of SEUs seem to demand that multiple, critical conditions (phantom commands, ACS upsets etc) may strike a single satellite at nearly the same time.

It still takes a long time to build a state-of-the-art satellite. The recovery and replacement time for satellite systems is not inconsequential, in the event of unanticipated, multiple satellite fatalities. For instance, it takes 12-14 months to build a Boeing-376 satellite bus according to *King* [2002], which is one of the most popular communications satellite buses now in service. If several dozen communications satellites have to be replaced to recover hundreds of failed transponders, this could be a significant near-term economic hardship, although

if the trends for increasing transponder over-capacity continue, it may simply result in a beneficial weeding-out of unused systems.

It is unlikely that the superstorm impact will be mitigated by a large increase in new satellite systems and capacity. The number of satellites launched in 2005-2024 will not be a constant rate, but by all forecasts, will increase slightly according to COMSTAC [2004]. Through the year 2013, it is expected that the annual satellite launches will increase from about 20 to 24, which will represent 211 new GEO satellite systems. Some of those will be for replacement of current, on orbit EOL assets. In fact, the demand for new satellites is declining due to the launch of more capable, multi-function spacecraft, so that many of the new satellite launches between 2004-2013 may be for replacing EOL satellite systems. The estimate we made in Section 3.0 for there being 181 GEO satellites older than 10 years by 2004 is similar to the COMSTAC new satellite launches of 211 by 2013, suggesting that most of these launches will be to replace retired EOL satellites. The 30 'new' satellites when compared to the 308 currently operating represent only a 10% net gain in GEO satellite capacity by 2013.

Satellite power continues to increase, as does solar panel voltages. Initially, engineers favored 28-50 volt systems, which do not favor the self-propagation of arcing events caused by high-energy cosmic rays and SPEs. Since 1995, satellite voltages have increased to over 100 volts, entering a domain in which solar panel arcing is self-propagating. This has caused several satellite systems to fail (for example, PAS-6 and Tempo-2 in 1997), forcing them to operate on only a fraction of their designed power. The trend towards higher power and higher voltage systems continues unabated, making them highly susceptible to space weather-generated avalanche failure.

The Space Station is planned to be abandoned sometime after 2014 just after the window for our Superstorm event closes. It may well be that there will be astronauts in continuous habitation of space at the time the superstorm arrives.

## **7.0 The Status of Warnings and Forecasts**

The National Weather Service portion of the National Oceanic and Atmospheric Administration (NOAA) along with the U.S. Air Force currently operates the Space Environment Center (SEC). SEC, located in Boulder, Colorado, provides real-time monitoring and forecasting of solar and geophysical events, conducts research in solar-terrestrial physics, and develops techniques for forecasting solar and geophysical disturbances. SEC continually monitors and forecasts near Earth space weather and is the Nation's official source for space weather alerts and warnings. SEC works with many national and international partners who contribute data and observations such as NASA.



NASA currently maintains a fleet of space science missions in both their prime mission phase and their extended mission phase as shown in Table 9. NASA extends their missions beyond their prime mission phase into an extended phase after they have achieved their original science objectives and only after they have demonstrated (every two to three years) that they can continue to contribute to other NASA strategic science objectives in a cost effective manner and remain relatively healthy. NASA space science missions provide significant amounts of data to SEC to support space weather predictions and warnings.

Advanced warning may be problematical because of the expected retirement of nearly all of the current NASA Sun-Earth Connection (SEC) fleet by 2008, and the slow launch of replacement systems to provide advanced warning, as summarized in Table 9. Although space weather research is an important part of NASA's strategic plan, by 2010 it is expected that NASA will no longer have ACE, SOHO, IMAGE, RHESSI, STEREO, and TRACE as operational space weather assets. Severe budget cuts have threatened to nearly eliminate NASA's current space weather research fleet of missions. Assuming no budget cuts or programmatic delays, by 2010 NASA will have GEO, SDO, Themis, MMS and GEC which will replace many, but not all, of the existing capacities. For example, the STEREO satellites are located well off the sun-earth line and would not provide *in situ* field measurements for earth-directed CME's as ACE currently does, though they would allow direct imaging of approaching CMEs. The arrival time of the CME could be calculated but not its geoeffectiveness (i.e. determined by Bz).

There will be no years of overlapping coverage during the main mission phases (indicated by L or P in the table) of these satellites. Only during the extended (E) mission phases will there exist the possibility for overlapping coverage.

Overlapping coverage is crucial for successful space weather forecasting. For example, the ACE satellite to be retired ca 2007 is stationed at L1 and provides about 1-hour notice of approaching CMEs as well as measures of their magnetic field orientation. It is also the case that these satellites will already be 5-9 years old by the next sunspot maximum, with the most intense storms likely to arrive even later in the cycle.

So far, NASA satellites have been able to detect CMEs, allowing space weather forecasters at NOAA/SEC to estimate their arrival times with reasonable half-day accuracy. However, a superstorm CME could take less than 17 hours to reach Earth. STEREO and SDO will continue this ability to monitor CMEs during the superstorm run-up. However, there will be no way to determine the magnetic field orientation of the CME en-route since, presumably, none of the satellites will be equipped with *in situ* magnetometers to study the interplanetary medium. This means we will have no advanced warning of the southward orientation of the ICME and therefore its geoeffectiveness.

Magnetic storms can be studied from the ground, however forecasting these events remains an illusive goal. According to statistics compiled by *Joselyn* [2001], forecasters can predict that a  $K_p > 4$  storm will occur on a particular day

with about 95% accuracy. However, the probabilities decrease to 45% in predicting a  $K > 5$  storm. Generally, more storms were detected (206) at a specific station (e.g. Fredericksberg) than were predicted (57) so that only 28% of the storms are actually predicted 24-hours in advance. Meanwhile, the number of false alarms was 62% which can have nearly as severe an economic impact as an actual storm, especially for electrical power grid operators subject to ground induced currents (GICs).

For satellites, however, it will not be the ICME or the ensuing geomagnetic storm that will provide the greatest immediate problem. X-ray flares and SPEs are the most destructive phenomena from the standpoint of satellite operations and power. For large events, CMEs are launched at the same time as the flares, so it is important to predict the flaring onset event before a halo-type CME is detected.

The sun produces about 20,000 C-class flares, 2,000 M-class events, 200 X-class events and fewer than 100 SPE events per solar cycle according to tabulations by *Joselyn* [2001]. Satellite X-ray and ground-based solar magnetic field imagers have provided 24-hour advanced notice on large flares. SPEs, often associated with strong X-ray flares, reach earth within hours after the x-ray flare is detected. For the most dangerous 'high rigidity' SPE spectra with cut-offs above 1 GeV, however, the particles are relativistic and arrive at virtually the same time as the x-ray burst so the onset of the x-ray flare is already too late an event for SPE mitigation to be effective. More research needs to be done to identify the solar magnetic fields and particle configurations that lead to flare events. Table 10 indicates the current records for X-class flare and SPE predictions among the most intense examples to date.

The most famous, and recent, of these events occurred on November 4, 2003. In the 5 days prior to the event, the 24-hour X-class flare probabilities [NOAA/SEC, 2003] were 50%, 40%, 35%, 75%, 75%. On the day of the flare, the probability remained at 75%, and in the three days after, dropped to 10%, 1%, and 1%. Although the X-ray class had been anticipated, neither the exact luminosity nor the day of the event had been predicted. Contrast this with the X-class event on April 15, 2001, which was only anticipated at a 25% probability. Including false-positives, the best estimate of 24-hour forecast reliability seems to be below 50% for X-class flares. This implies a 1 in 2 chance a major X-class 'superflare' could not be anticipated within 24-hours of the event.

Would a superflare birth site have a distinctly different magnetic signature in a solar active region so that the forecast could be made more accurate? This is currently unknown. We do know that the 1859 event coincided with an impressively large sunspot group near meridian transit. These are also conditions that have been more impressively manifested for lesser storm events. Currently, space weather forecasters consider any large sunspot in the 1859-class a potential threat for the roughly 2 weeks that it is present on the earthward side of the sun, and especially threatening during the 5-days near solar meridian transit. Currently, this may well be the best advanced warning we can achieve.

## 8.0 Conclusion

All indications point to a potentially major economic and military impact of our space assets for the next major 1859-like superstorm event. Unlike previous historical events, our current reliance on satellite technology and human activities in space, place us in a unique and unprecedented nexus of vulnerabilities from such an event.

Although it is difficult to accurately assess the economic consequences due to incomplete data on military and commercial satellite systems, we can nevertheless bound the likely impacts by a worst-case scenario involving a superstorm about 3-fold more severe than the 1859 Carrington-Hodgson event. This scenario includes a \$5 to  $10 \times 10^9$  financial impact on commercial satellite systems due to a combination of direct hardware loss, service loss and indirect profit loss. Satellite engineers and operators will experience thousands of satellite anomalies per day across the satellite fleet— an unprecedented rate never-before experienced during the space age. There may be a significant loss of operating satellites numbering perhaps 50 - 80 as a result of older systems already past their designed lifetime radiation dosages, being impacted by a large new influx of radiation equal to 3 to 5 more years of annual dosage. The SPEs from the superstorm result in a sharp rise in mission-critical anomalies in satellite power and orientation systems, which lead to complete satellite failure, especially for GEO and MEO satellites that are not as atmospherically well shielded as LEO systems. For satellites younger than about 5 years, the superstorm may actually double their accumulated dosages to date, and halve their operating lifetimes.

Current GPS systems will be rendered temporarily, or perhaps even permanently, unusable with, at the minimum, very large position errors perhaps approaching 100-meters being common for 24-72 hours. Unless the new generation Block IIM systems are in place, which are able to compensate for ionospheric TEC variations, the GPS system may effectively go off-line for many civilian and military applications. There is also the possibility that a number of the older GPS satellites may fail so that the full compliment of 24 satellites will be unavailable in the months and years immediately following the storm. This means that even ionosphere-compensated position measurements may not be available for portions of the day when the requisite four to six satellites are not above the horizon for specific geographic locations. The realization of the expected position errors for military use with a minimum of four satellites above the horizon, will be a complex function of local time and geographic location requiring a detailed ephemeris to implement. It may take months or years to restore the GPS system to full operating status, depending on the number of satellite failures involved.

The International Space Station, will undoubtedly experience a significant loss in altitude exceeding the 15 km decrease experienced during the Bastille-Day Storm. Existing re-boost systems can produce a maximum of only about 70 km of perigee change. If the superstorm occurs at the peak of the next sunspot maximum when re-boots are more frequent and larger in magnitude, the

required post-superstorm reboost may be at the limits of what can be accomplished during a single mission. The specific details depend on the amount of atmospheric heating and the duration of the superstorm event. There may also be an increased risk of collision by the ISS with in-bound satellites affected by the temporarily increased atmospheric drag. Approximately 22 operating LEO satellites are currently in orbits that could be severely affected by superstorm atmospheric heating and high-drag conditions, and which could reach or pass through the ISS altitude range on de-orbit trajectories. Moreover, an additional 98 LEO satellites, worth an estimated  $\$1.6 \times 10^{10}$ , may prematurely re-enter by 2021. Although many of these systems will doubtless have been replaced, thereby minimizing the economic and scientific impacts, their re-entry at this time will have been unplanned and premature by several decades at the normal rates of orbit decay.

Our resources for forecasting such a superstorm using NASA and NOAA assets will be covered by a complicated constellation of satellites whose overlapping years will be generally well-beyond their planned mission lifetimes. These satellites will be relatively old systems near the end of their maximum lifespans. Unlike the coverage we have experienced during Cycle-23, the next sunspot cycle will be significantly more problematical.

Our forecasting methodologies today must significantly improve, or the pre-conditions for a superstorm may actually be missed. There is currently a better than 50/50 chance that the X-ray and SPE events associated with a superstorm may not be anticipated in time to allow satellite operators to mitigate their worst impacts. Forecasts of the level of the geomagnetic effects, and the severity of the storm, may also lack certainty in the 24-hours leading up to the storm. The event may, however, be preceded by several days of false-positive forecasts, which may have the undesirable effect of rendering satellite engineers and operators less engaged when the actual event arrives.

If the events of the 1859 superstorm serve as a guide, the scope of the storm will most certainly be an awesome event in our modern history, but one that the vast majority of our satellite resources may reasonably be expected to survive. Nevertheless, there will be a considerable number of satellite systems that will be inevitably damaged, or seriously degraded in operating lifetime and profitability.

## **Acknowledgments**

The research for this paper was accomplished under NASA Contract NNG04EA43C.

## **References**

- Allen, J.H. and Wilkinson, D.C. 1993, "Solar-Terrestrial Activity Affecting Systems in Space and on Earth", in Proceedings of the Workshop on Solar-Terrestrial Predictions, Ottawa, Canada, 18-22 May, 1992.

- Baker D.N., 1986 "Effects of the Solar-Terrestrial Environment on Satellite Operations", in Proceedings of the Solar-Terrestrial Predictions Workshop", Meudon France, 18-22 June 1984.
- Baker D.N., et al. 1997, "Recurrent Geomagnetic Storms and Relativistic Electron Enhancements in the Outer Magnetosphere", *J. Geophys. Res.*, vol. 102, pp. 14141-14148.
- Brekke, P. 2004, "Space Weather Effects on SOHO and its Space Weather Warning Capabilities", in 'Effects of Space Weather on Technology Infrastructure', Ioannis Daglis Ed. (Kluwer Academic Publishers: Boston).
- Belov, A. et al., 2004, "The Relation of High and Low-Orbit Satellite Anomalies to Different Geophysical Parameters", in 'Effects of Space Weather on Technology Infrastructure', Ioannis Daglis Ed. (Kluwer Academic Publishers: Boston), pp. 147-164.
- Chetty, P. R. K. 1991, 'Satellite Technology and its Applications', 2ed. (McGraw-Hill). pp. 164-166.
- Cliver, E.W. and Svalgaard, L, 2005, "The 1859 Solar-Terrestrial Disturbance and the Current Limits of Extreme Space Weather Activity", *Solar Phys.*, vol. 224, No. 1-2, pp. 407-422.
- COMSTAC: Commercial Space Transportation Advisory Committee, 2004, '2004 NGSO Commercial Space Transportation Forecasts', May 2004, (<http://ast.faa.gov>).
- Crabb, R.L., 1994. Solar Cell Radiation Damage, *Radiat. Phys. Chem.* Vol. 43, pp. 93-103.
- Editors, 1859, *Am. J. Sci.*, vol. 28, pp.385-408.
- Editors, 1860, *Am. J. Sci.*, vol. 29, pp. 92-97, 249-265, 386-397.
- Encyclopedia Astronautica, 2005, <http://www.astronautix.com/index.html>
- Futron Corporation, 2003, "How Many Satellites are Enough?" <http://www.satelliteonthenet.co.uk/white/futron5.html>
- Global Defence, 2001, <http://www.global-defence.com/2001/LSpart4.html>
- GPS World, February 2004, [http://www.w2forum.com/item/global\\_market\\_top\\_22\\_billion](http://www.w2forum.com/item/global_market_top_22_billion)
- GPS World, 2004 October 1, "Combating the Perfect Storm" by Richard Langley. <http://www.gpsworld.com/gpsworld/article/articleDetail.jsp?id=128321&pageID=7>
- GPS Fact Sheet, 2000, [http://www.losangeles.af.mil/smc/pa/fact\\_sheets/gps\\_fs.htm](http://www.losangeles.af.mil/smc/pa/fact_sheets/gps_fs.htm)

Green, J. L. and S. A. Boardsen, 2005, Duration and extent of the Great Auroral Storm of 1859, Submitted to *Adv. Sp. Res.*

Guenthers Space Page, 2005 [www.space.skyrocket.de](http://www.space.skyrocket.de)

Hammons, C. 2001 'A Study of the Effects of Large Solar Events on the Atmospheric Drag of Low Earth Orbiting Satellites',  
[http://ccar.colorado.edu/asen5050/projects/projects\\_2001/hammons/](http://ccar.colorado.edu/asen5050/projects/projects_2001/hammons/)

HeavensAbove.com, 2005, 'Orbit decay plot for Starshine-3', <http://heavens-above.com>

Joselyn, J. 2001, "State of the Art in Space Weather Services and Forecasting",  
", in 'Space Storms and Space Weather Hazards', I.A. Daglis (ed.), p. 419,  
(Kluwer Academic Press : Netherlands).

JSC, 2002, "ISS Environment: ISS Payload Information Source", Johnson  
Spaceflight Center, <http://stationpayloads.jsc.nasa.gov/D-aboutiss/D6.html>

King, 2002 : [www.mrcmicroe.com/MAYCOMB2.pdf](http://www.mrcmicroe.com/MAYCOMB2.pdf)

Loomis, E., 1860, *Am. J. Sci.*, Vol. 30, pp. 79-94, 339-361.

Loomis, E., 1861, *Am. J. Sci.*, Vol. 32, pp. 71-84, 318-331.

Lucci, A.E. et al., 2005, 'Space Weather Conditions and Spacecraft Anomalies in Different Orbits', *Space Weather*, Vol. 3, S01001, doi:10.1029/2003SW000056.

LyngSat.com, 2005, <http://lyngsat.com/>

McCracken, K.G., G.A.M. Dreschhoff, E.J. Zeller, D.F. Smart, and M.A. Shea,  
2001a, 'Solar Cosmic Ray Events for the Period 1561-1994', *J. Geophys. Res.*, Vol. 106, pp. 21585-21598.

McCracken, K.G., G.A.M. Dreschhoff, D.F. Smart, D.F. Smart, and M.A. Shea,  
2001b, "Solar Cosmic Rays for the Period 1561-1994; The Gleissberg periodicity", *J. Geophys. Res.*, Vol. 106, pp. 21599-21610.

Messerschmid, E. and Bertrand, R. 1999 'Space Stations, Systems and Utilization', (Springer, Heidelberg) p.224.

Mountford, T.M.P, and Sastry, V.S.S., 2000. 'On the Prediction of Anomalous Events Onboard Geostationary Spacecraft'  
[http://ms.ie.org/SIW\\_LOG/03F/03F-SIW-019.doc](http://ms.ie.org/SIW_LOG/03F/03F-SIW-019.doc)

NASA, 2005, "ISS Perigee Height",  
<http://www.hq.nasa.gov/osf/station/viewing/history.html>

- NOAA, 2005, <http://www.sec.noaa.gov/weekly/weekly03.html>
- NOAA, 2004, "Solar Proton Events Affecting the Earth Environment"  
<http://www.sec.noaa.gov/alerts/SPE.html>
- Odenwald, S.F., 2000, 'The 23rd Cycle: Learning to live with a stormy star', (Columbia University Press: NY).
- Odenwald, S.F. 2005, "Space Weather: Technological and Human Impacts",  
<http://www.spaceweather.us>
- Panasyuk, M.I. 2001, "Cosmic Ray and Radiation Belt Hazards for Space Missions", in 'Space Storms and Space Weather Hazards', I.A. Daglis (ed.), p. 251, (Kluwer Academic Press: Netherlands).
- Patel, M. R. 2000, 'Spacecraft Power Systems', (CRC Press, New York), p.115.
- Reedy, R. 1998, "Solar Particle Events and their Radiation Threats", in the 'Conference on the High Energy Radiations Backgrounds in Space', IEEE Nuclear and Space Radiation Effects Conference', Snowmass, Colorado, July 22-23, 1997.
- Robertson, B. and Stoneking, E. 2003, AAS Guidance and Control Conference, AAS-03-071, and 'Guidance and Control 2003', Robert D. Culp and Ian J. Gravseth (Eds.), Univelt, Inc, ISBN: 0877035032.
- Sat-ND.com, 2005, <http://www.Sat-ND.com>
- Science@NASA, 2000, 'Solar Activity Puffs Up Atmosphere'  
[http://science.nasa.gov/headlines/y2000/ast30may\\_1m.htm](http://science.nasa.gov/headlines/y2000/ast30may_1m.htm)
- Science@NASA, 2001, A Disco Ball in Space,  
[http://science.msfc.nasa.gov/headlines/y2001/ast09oct\\_1.htm](http://science.msfc.nasa.gov/headlines/y2001/ast09oct_1.htm)
- Skone, S., El-Gizawy, M. and Shrestha, S. M. "Analysis of differential GPS performance for marine users during solar maximum, Radio Sci., 39, RS1S17. [www.agu.org/journals/rs/rs0401/2002RS002844/2002002844.pdf](http://www.agu.org/journals/rs/rs0401/2002RS002844/2002002844.pdf)
- SNOE Team, 2004, <http://www.spaceweather.us/Svulnerability.html>
- Space.com, 2003, April 9, [http://www.space.com/news/nss\\_sia\\_030409.html](http://www.space.com/news/nss_sia_030409.html)
- Space News, 2002, 'Japanese facing uphill battle to save damaged spacecraft, Sept 22.
- Spacetoday.net, 2005 "Progress Increases ISS Orbit",  
<http://www.spacetoday.net/Summary/2798>
- SpaceRef.com, 2003, April 18 "Space Station Science Picture of the Day: Reboost", <http://www.spaceref.ca/news/viewstr.html?pid=8869>

SpaceRef.com, 2003, 'Expected Hubble Space Telescope Science Lifetime after SM4', HST Program Office, July 21, 2003,  
<http://www.spaceref.com/news/viewsr.html?pid=9911>

Space Track, 2005, <http://www.space-track.org/perl/login.pl>

Spotts, P, 2003, Christian Science Monitor, Aerospace Corporation Study.  
<http://www.csmonitor.com/2003/1009/p11s02-stss.htm>

Stephens, D. L. et al., 2004 "Interplanetary Crew Dose Estimates for Worst Case Solar Particle Events Based on the Historical Data for the Carrington Flare of 1859, *Acta Astronautica*, Vol. 56, p. 969-974.

The Satellite Encyclopedia, 2005, <http://www.tbs-satellite.com/tse/online/>

Todd, L. and T. Bowling 2004, 'Debris Mitigation in Geostationary Earth Orbit', Cranfield Space Research Center,  
<http://www.cranfield.ac.uk/soe/space/publications.htm>

Townsend, L. W. et al., 2005, "The Carrington Event: Possible Doses to Crews in Space from a Comparable Event", Submitted to *Adv. Sp. Res.*

Townsend, L. W., 2003 "Carrington Flare of 1859 as a Prototypical Worst-Case Solar Energetic Particle Event", *IEEE Transactions on Nuclear Science*, Vol. 50, p. 2307-2309.

Tsurutani, B.T., W. D. Gonzalez, G. S. Lakhina, S. Alex, The extreme magnetic storm of 1–2 September 1859. *J. Geophys. Res.*, Vol. 108, No. A7, 1268.  
<http://www.agu.org/pubs/crossref/2003/2002JA009504.shtml>

VSAT, 2005 "Satellite Internet Costs", <http://www.satsig.net/ivsaticos.htm>

Webb, D. and Allen, J. 2004, "Spacecraft and Ground Anomalies Related to the October-November 2003 Solar Activity", *Space Weather*, Vol. 2, S03008, doi:10.1029/2004SW000075.



Table 1 – Statistics for Working Satellites ca 2004.

Location	Com Sats	Military	Research	Total operating Satellites
LEO	273	94	70	437
MEO	19	101	12	132
GEO	308	51	8	367
Totals	600	245	91	936

Table 2 Commercial transponder rental rates

Satellite	Bandwidth	Rental Rate per year \$10 <sup>6</sup>	Usage
INSAT-2E	36, 72 MHz	\$1.5	INTELSAT lease to customers
Skynet	36 MHz	\$1.4	Average for 7 existing satellites in 2002.
SBS-6	36 MHz	\$3.1	Ku-band leased for \$350/hr
Telstar-5	27 MHz	\$2.1	Auctioned at \$175,000/mo
Telstar-5	54 MHz	\$3.1	Auctioned at \$255,000/mo
SatMex-5	36 MHz	\$2.3	Auctioned at \$195,000/mo

Table 3: SPE fluences in pfus for 1976 - 2004

Year	Peak	Date	X-flare
1976	12 pfu	May 1	X2
1977	200	Sep 19	X2
1978	2200	Sep 23	X1
1979	950	Jun 7	X2
1980	100	July 19	M3
1981	2000	Oct 13	X3
1982	2900	July 13	X9
1983	340	Feb 4	X4
1984	2500	April 26	X13
1985	160	April 26	X1
1986	130	Feb 14	X1
1987	120	Nov 8	M1
1988	92	Jan 3	X1
1989	40000	Oct 20	X13
1990	950	Mar 19	X1
1991	43000	March 24	X9
1992	4600	May 9	M7
1993	44	Mar 13	M7
1994	10000	Feb 21	M4
1995	63	Oct 20	M1
1996	0		
1997	490	Nov 7	X9
1998	1700	April 21	M1
1999	64	June 4	M3
2000	24000	July 15	X5
2001	31700	Nov 6	X1
2002	2520	April 21	X1
2003	29500	Oct 29	X17
2004	2086	July 26	M1

Table 4: Operational status of oldest GEO satellites by 2005

Satellite	Age	Predicted Power	Transponders	Status
Marisat-3	28	11	2	Operating.
Farrah-5	20	29	???	Unknown
SBS-4	20	29	14	Operating
DSCS 3A2	19	31	7	Operating-Military
DSCS 3A3	19	31	7	Operating-Military
DSCS 3B5	19	31	7	Operating-Military
Brasilsat-A2	18	33	30	Replaced 2000
Optus-A3	17	35	15	Operating
Spacenet-3	16	35	28	Replaced 1996
TDRS-3	16	37	48	Operating
Marecs-3	16	37	???	Unknown
DSCS 2-15	15	39	???	Operating-Military
Intelsat-602	15	39	64	Operating.
Marecs-4	15	39	???	Unknown
TDRS-4	15	39	48	Operating
FLTSATCOM-8C	15	39	12	Operating-Military
DSP 3-2	14	49	???	Operating- Military
Asiasat-1	14	49	24	Replaced 1999
DSP 3-3	14	49	???	Operating-Military
Inmarsat-2F1	14	49	8	Operating
Intelsat-604	14	49	38	Replaced in 2002
Palapa B2R	14	49	30	Operating
SBS-6	14	49	14	Operating
Skynet 4A	14	49	7	Operating-Military
Skynet 4C	14	49	7	Operating-Military
Leasat-5	14	49%	13	Operating-Military

Table 5 Major Historical Storm Rankings

Date	CME Transit Time (hrs)	SPE proton fluence ( $10^9/\text{cm}^2$ )	Dst (nT)	SID (nT)	Auroral Latitude (degrees)	Flares
Nov 4, 2003				115		X34
Sep 1, 1859	17.6	18.8	-1760	110	20	White light
Aug 4, 1972	14.6	5.0				
Oct 28, 2003	20.3					> X17
Feb 11, 1958			-428		28	
Feb 4, 1872					19	
Mar 14, 1989			-548			

Table 6: SPE events and their correlation with the sunspot maximum

SPE Year	Fluence	Sunspot Max	(SPE-Max)
Aug 12, 1989	9,200 pfu	1989.6	0.0 yrs
Oct 19, 1989	40,000	1989.6	+0.2
Mar 23, 1991	43,000	1989.6	+1.3
Feb 20, 1994	10,000	1989.6	+4.6
July 14, 2000	24,000	2000.5	+0.1
Nov 8, 2000	14,800	2000.5	+0.3
Sept 24, 2001	12,900	2000.5	+1.3
Nov 4, 2001	31,700	2000.5	+1.4
Nov 22, 2001	18,900	2000.5	+1.5
Oct 28, 2003	29,500	2000.5	+3.3

Table 7: Fitted orbit decay constants

Satellite	Mass	Perigee	Solar Maximum		Solar Minimum	
		$P_0$	A	$\alpha$	A	$\alpha$
SNOE	115 kg	580 km			1.3	0.18
HST	14,000	575	0.7	0.27		
ASCA	420	570	0.2	0.24		
Starshine-3	80	475			1.5	0.6
ISS	470,000	395	1.0	0.6	1.1	0.4

Table 8: Possible ISS orbit-crossing candidates.

Satellite	Launch	Perigee at launch (km)	Predicted Re-entry Year
Swift	2004	600	2013
ZY 2-3 (ZY-2C)	2004	472	2011
XSS-10	2003	518	2010
IGS-1A	2003	500	2010
Orbview-3	2003	470	2010
Cosmos 2405	2004	402	2010
ZY 2-2	2002	472	2009
RHESSI	2002	520	2008
GRACE-2	2001	500	2008
KORONAS-F	2001	500	2008
GRACE-1	2001	483	2008
QUICKBIRD-2	2001	460	2008
Ofeq-5	2002	370	2008
ZY 2-1	2000	472	2007
Cosmos-2383	2001	402	2007
Sicral 1	2001	328	2007
Cute-1	2003	320	2007
Rocsat-1	1999	600	2006
Ziyuan-2	1999	483	2006
EROS-A1	2000	480	2006
CHAMP	2000	400	2006
FSW 3-3	2004	284	2006
Mikron	2004	282	2006
COROLIS	2003	278	2006
NROL-1	2004	260	2006
TRACE	1998	602	2005

Table 9 - Current and Future Sun-Earth Missions

	SHO	WND	POL	ACE	TRA	IMG	TIM	HES	STE	TWN	THM	SoIB	MMS	SDO	GEC	GOES
1995	L	P														
1996	P	P	L													
1997	P	E	P	L												
1998	P	E	P	P	L											
1999	E	E	E	P	P											
2000	E	E	E	E	P	L										
2001	E	E	E	E	E	P	L									M
2002	E	E	E	E	E	P	P	L								P
2003	E	E	E	E	E	E	P	P								P
2004	E	E	E	E	E	E	P	P	L							P
2005	E	E	E	E	E	E	E	E	P	L						N
2006	E	E	E	E	E	E	E	E	P	P	L	L	L			P
2007	E	E	E	E	E	E	E	E	E	P	P	P	P	L		O
2008						E			E	E	P	P	P	P	L	P
2009									E	E	E	E	E	P	P	P
2010									E	E	E	E	E	E	P	P
2011									E		E	E	E	E	E	P
2012									E		E	E	E	E	E	R
2013									E		E	E	E	E	E	P
2014									E		E	E	E	E	E	P
2015									E		E	E	E	E	E	

Note: HES=RHESSI, TRA=TRACE, TWN=TWINS, IMG=IMAGE, POL=Polar, TIM=TIMED, SHO=SOHO, STE=STEREO, THM=THEMIS and WND=WIND. Launch years for the GOES-series are indicated by M, N, O, P and R respectively. L=Launch year, P=planned (budgeted) mission year, and E=extended mission year subject to NASA approval. The shaded zones correspond to sunspot maximum conditions between 1999-2001 and expected to be 2011-2013.

Table 10 Some recent X-Class Flare Predictions

Date Predicted	Date of Actual Event	Predicted Strength	Actual Strength
11-2 to 11-4 : <b>75%</b> probability in next 24-hrs	11-4-2003	X-class	X20+
10-26 to 10-31 <b>50%</b> prob. In next 24hrs.	10-28-2003	X-class	X17
4-9 to 4-14 <b>25%</b> in next 24-hrs	4-15-2001	X-class	X14
4-2: <b>35%</b> chance in next 48 hours	4-2-2001	X-class	X20

Reference: [www.spaceweather.com](http://www.spaceweather.com) and NOAA/SEC



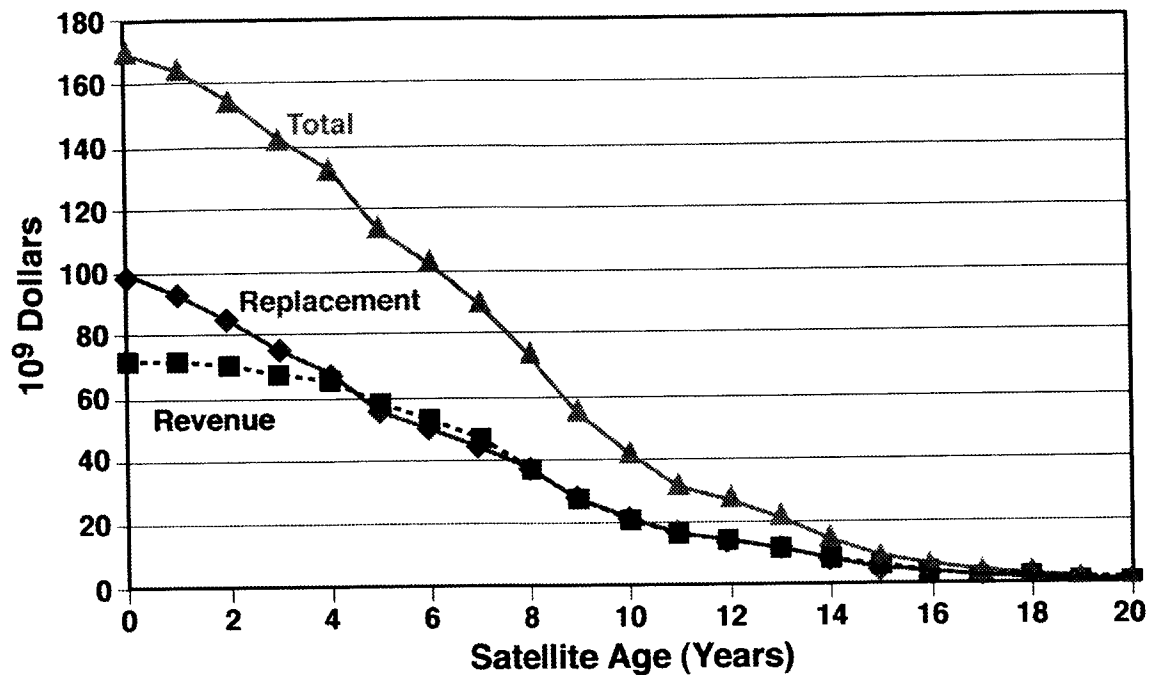


Figure 1: Cumulative value of the GEO satellites with ages less than 20 years by 2004. The total value (dots) is a combination of the replacement cost, including launch, of the satellite (diamonds), and the revenue generated from the satellite transponders in service (squares).

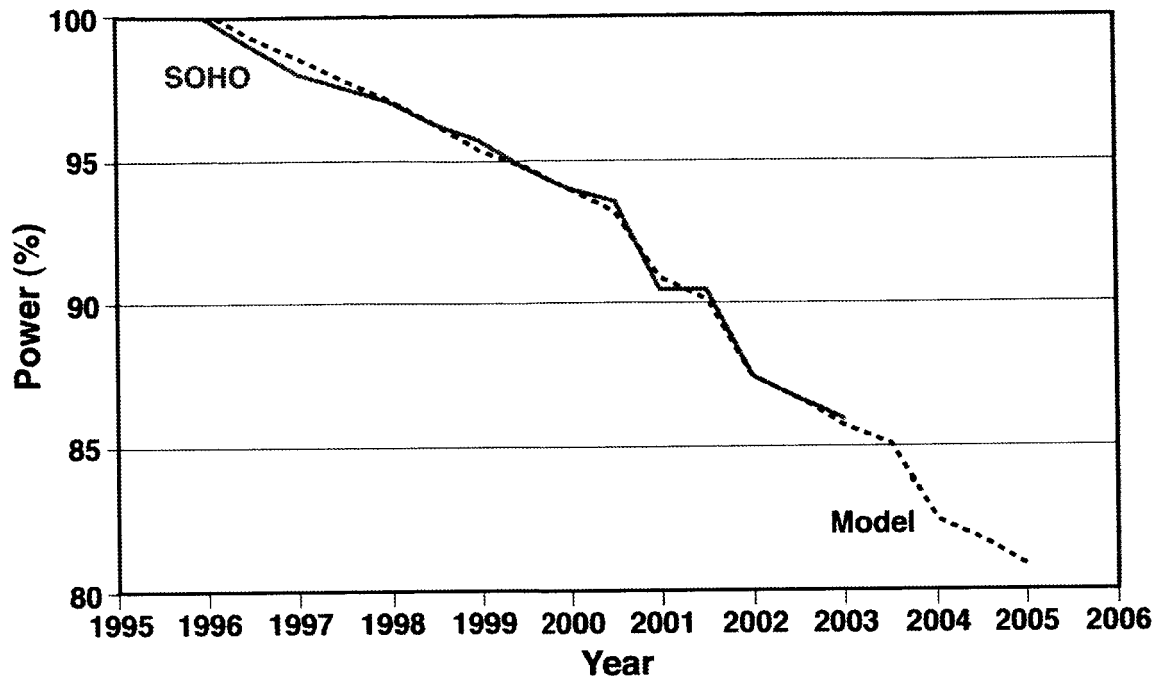


Figure 2: SOHO satellite operating power (blue solid line) compared to a model (dashed line), including cosmic ray and SPE degradation. SOHO data adapted from *Brekke* [2005].

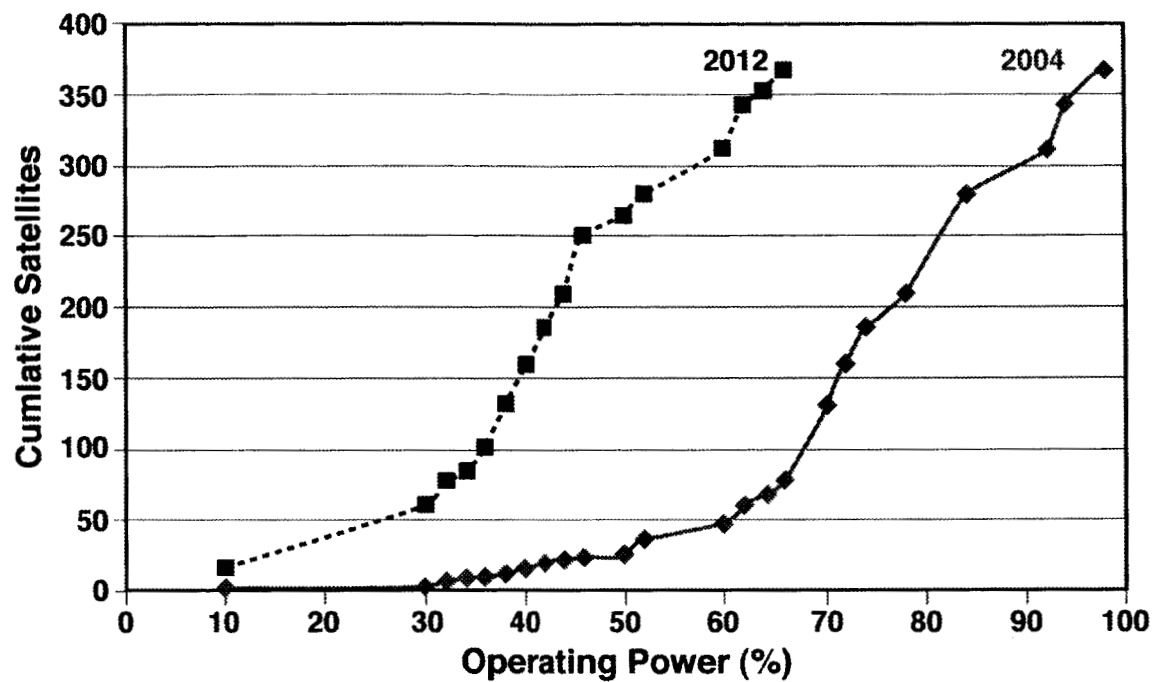


Figure 3: Cumulative GEO satellite population size compared to operating power for 2004 (blue diamond points) and 2012 (black square points).

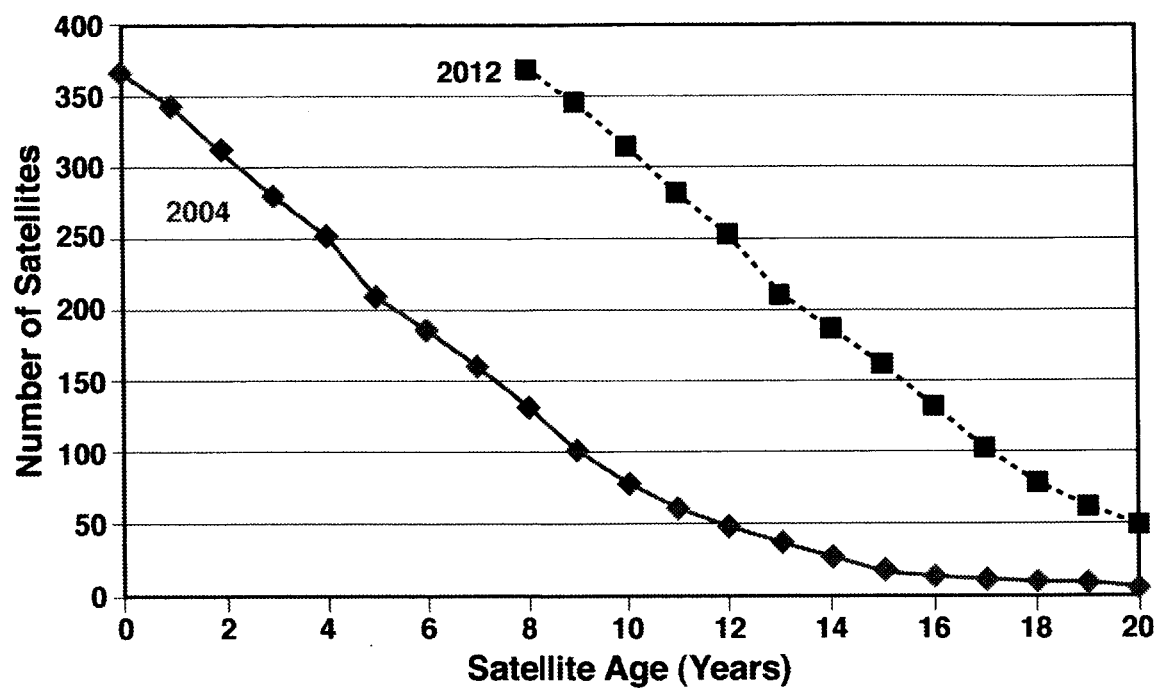


Figure 4: Cumulative GEO satellite ages for 2004 (blue diamond points) and 2012 (black square points).

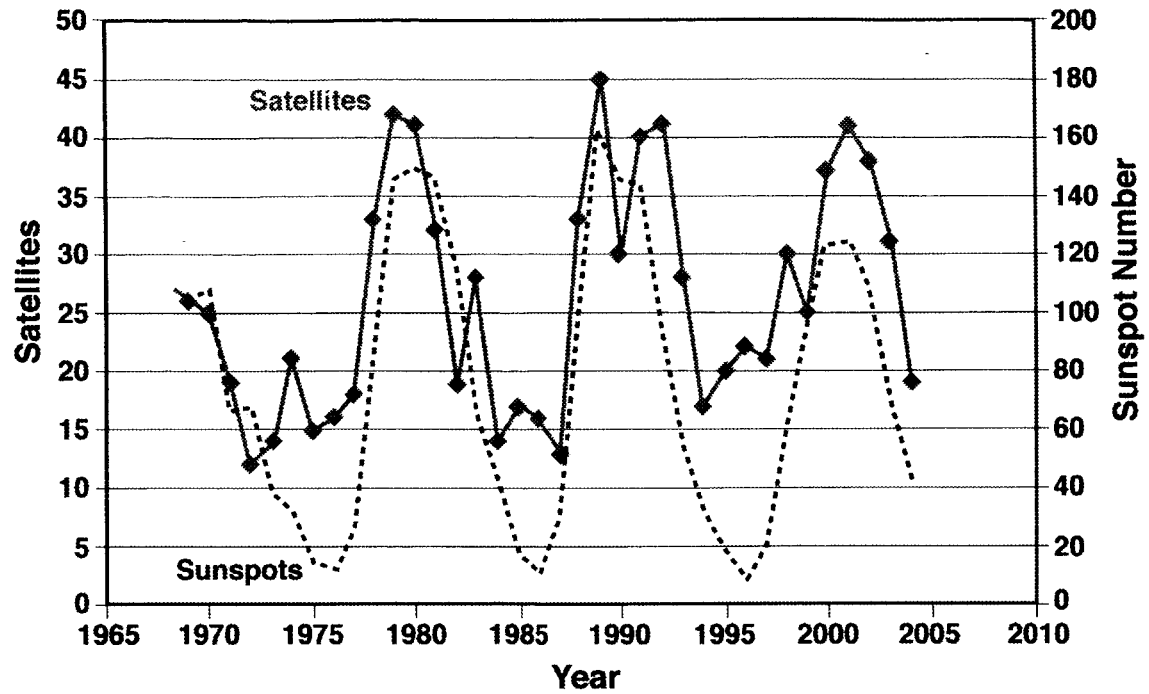


Figure 5: Satellite de-orbits (blue solid line) compared with solar activity cycles from 1967-2004 (black dashed line).

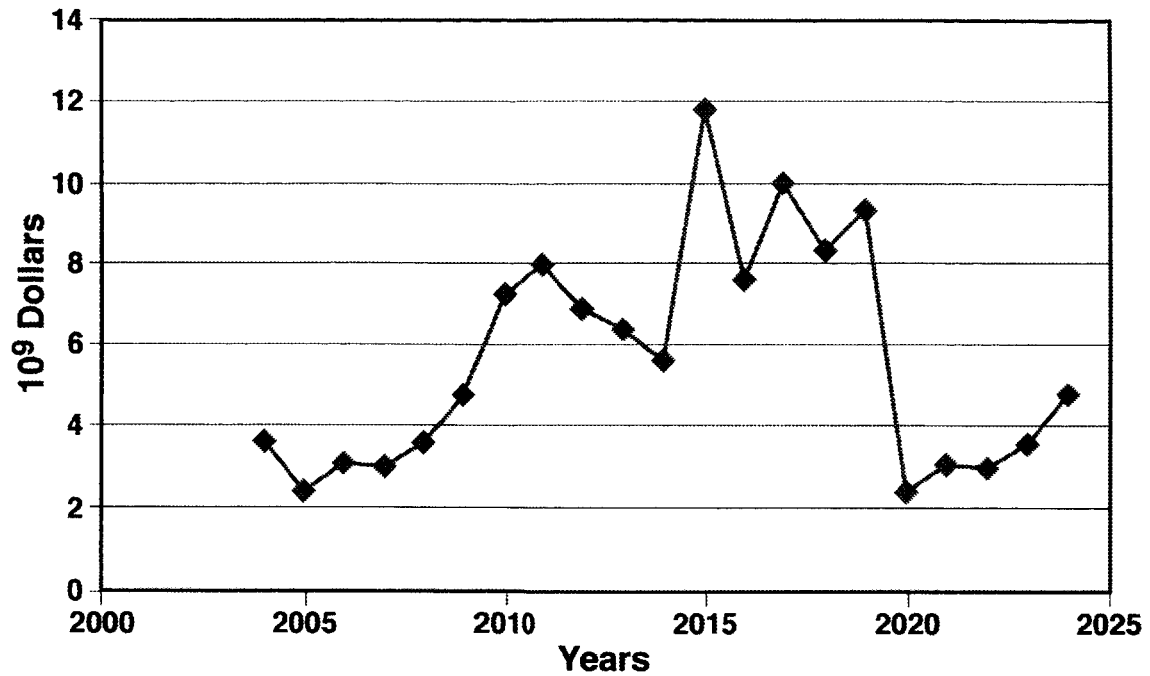


Figure 6: Distribution of replacement costs for GEO satellites assuming a 15-year lifetime.

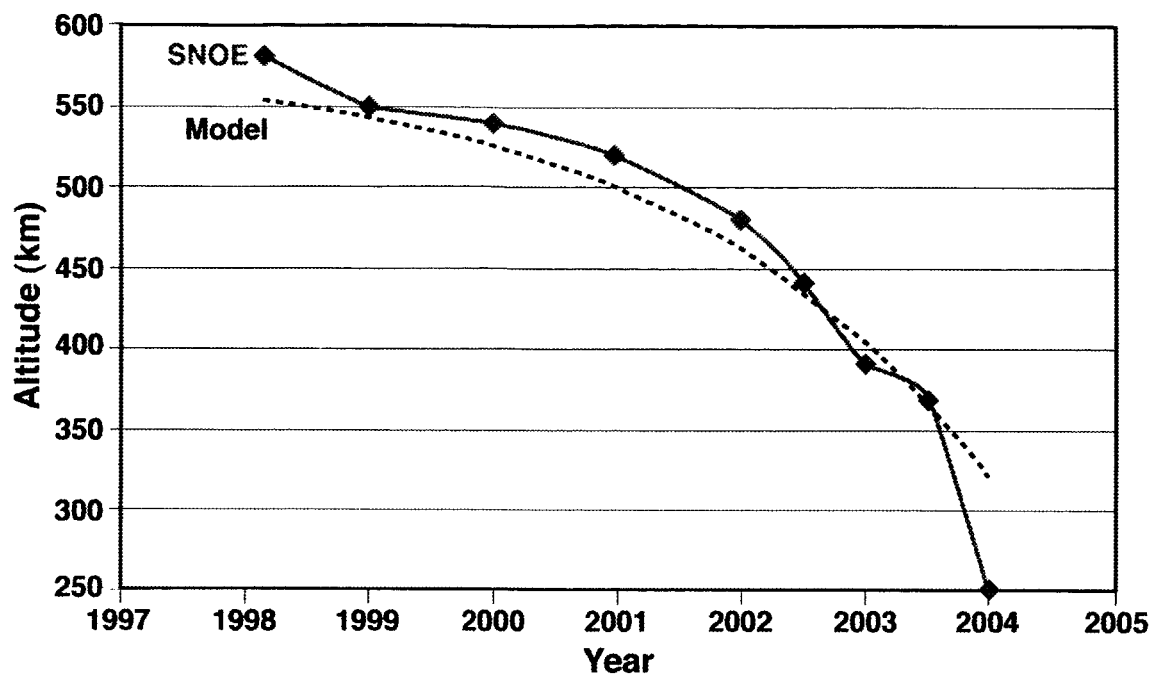


Figure 7: Comparison of SNOE satellite decay altitude profile, with a simple power-law model. Satellites with perigees below 300 km de-orbit within 1-year. A precise orbit evolution is not needed for the current analysis, which involves a 100-km binning resolution.

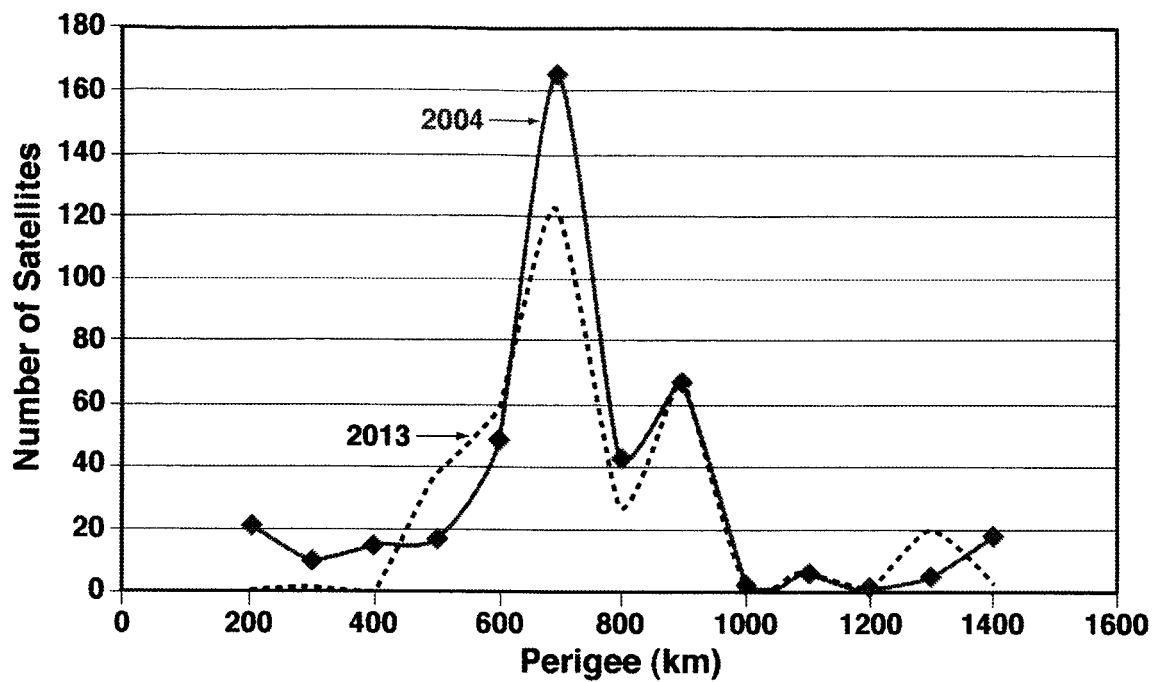


Figure 8: Distribution of LEO satellite orbits by 2004 (blue solid line) and predicted 2013 (black dashed line) with 100-km perigee binning. Variations in the >1200 km bins are spurious, and caused by 1-km shift in modeled satellite perigees across binning boundary.



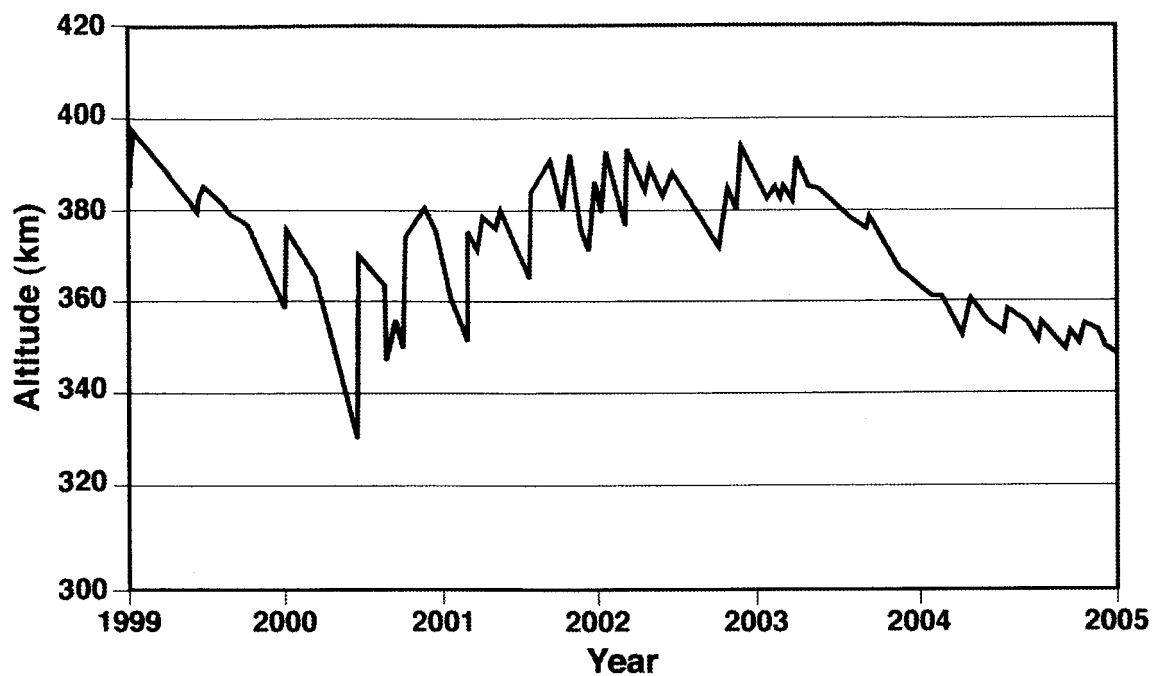


Figure 9: International Space Station altitude evolution between 1999-2005 adapted from NASA [2005]. Orbit decay rates are  $\sim 400$  meters/day at solar maximum and  $\sim 90$  meters/day near solar minimum.